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Smart Street Lighting over Narrowband PLC in a Smart City: The Triangulum Case Study.

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***Abstract*—As municipalities continue to embrace digital revolution in a bid to become *smarter cities*, the unique intersection between ICT and development road map is inspiring new innovative applications. While this quest for smart city continues, the transformation of street lighting has become a topical issue. As part of ongoing investigation in Triangulum smart city project, this paper presents some simulation results on the use of narrowband powerline communication (NPLC) for street lights monitoring and control. The results show that, with low power, NPLC can support a 3.5km network of street lights without using a relay. It is also shown that, when the data packet size quadruples, latency degrades by up to 22.63% (242.03ms) in the worst case.**

***Keywords*—Narrowband PLC; smart street lights; smart city.**

I. INTRODUCTION

Street lighting is an important public service making communities more habitable for modern living. However, traditional lamps are not energy-efficient and their management largely remains a challenge [1], [2]. Traditionally, streetlights were controlled by simple circuits containing light dependent resistor (LDR). The LDR being a photo-resistor changes its electrical resistance from several thousand ohms in the dark to a few hundred ohms in the presence of light. This mechanism is used to vary the operational states of street lamps from “OFF” to “ON” and vice-versa [1], [3] .

The use of LED has been widely applauded as a suitable replacement, given that they are more energy-efficient and eco-friendly. Key advantages of LEDs include: i) they do not contain toxic chemicals such as mercury[4], ii) very long life span (sometimes 100,000 hours), as they do not contain filaments like traditional high-pressure sodium lamps which burn out quickly [2], [4] and iii) low maintenance cost which is particularly suitable for suburban and hard-to-reach locations where frequent replacement of bulbs is expensive, risky or inconvenient. These LED features are constsitent with EU 20-20-20 strategic objectives to reduce green house gas emission by 20%, increase renewable uptake by 20% and improve energy efficiency by 20% by year 2020 [5] and low-carbon vision 2050.

Although, the smart city idea incorporates dissimilar elements using the power of information and communication technology (ICT), it also presents a new opportunity to address some old challenges. For example, improper street lighting has been found to contribute significantly to energy wastage and light pollution in many cities in the world [5]. Further, in some parts of Europe, outdoor lighting accounts for approximately 20% of cities’ electricity bills [5]. It has also been observed that while lighting accounts for 19% of energy use globally, it contributes about 6% of greenhouse gases (GHG) [2]. Hence, improvement in lighting control systems can lead to reduction in GHG emissions.

In addition to the advantages of LED enumerated above, the major benefit of monitoring the street lamps is that their status and operational states can be remotely observed from a central location, thereby making it possible to identify and reduce the cost of potential failures. Underpinning such *smartness* is a bi-directional communication system, inexpensive, yet scalable to meet the required communication needs. Considering the number of street lights in cities, this large scale transformation presents some interesting technical challenges.

Power line is regarded as as a viable communication channel for many applications including smart grid [6], [7]. Power line communication (PLC) utilises existing power lines to transmit information in addition to its traditional use for power delivery thus eliminating the cost of dedicated data cables or antenna. PLC systems can be grouped in terms of frequency into ultra narrowband (125 – 3000 Hz), narrowband (3-500kHz) and broadband (1.8 – 100MHz) [8]. While broadband PLC (BPLC) yields data rate of hundreds of Mbps and covers a few hundreds of meters, narrowband PLC (NPLC) generally delivers data rate of a few hundred of kbps but over several km. This longer range of NPLC renders it more suitable for outdoor applications such as smart metering [7] and street lighting over LV lines in a smart city. At application layer, these data rates reduce to some tens of kbps and tens or few hundreds of Mbps for NPLC and BPLC respectively[9].

The contribution of this paper is not only exploitation of NPLC for cases where wireless communication is difficult or uneconomical, the results also provide some insights into the feasibility of NPLC for monitoring other street furniture such as traffic lights, telephone booths, etc. In fact, since the power lines already exist, strategic street light poles could be fitted with LCD to display near real-time traffic update and weather forecast without having to install dedicated wireless local area network (WLAN) or additional radio units. The remainder of this paper is organised as follows.

Triangulum and related works on smart city are discussed in Section II while Section III describes our simulation setup. Section IV presents our simulation results and finally, the key conclusions are discussed in Section V.

II. TRIANGULUM AND RELATED WORKS ON SMART CITY

The Triangulum project is an European Commission's Lighthouse project with the overall objective of transforming selected cities into smart quarters. As the first three lighthouse cities, Stavanger (Norway), Manchester (UK) and Eindhoven (Netherlands) have been selected as test beds, focusing on sustainable mobility, energy and ICT. Currently constituted by a consortium of 22 partners drawn from industry, municipalities and research community, the outcomes are to be replicated in Prague (Czech Republic), Leipzig (Germany) and Sabadell (Spain), being the follower cities. Pooling these vast resources together, the consortium is expected to develop and implement smart solutions with a view to improving sustainability and quality of life of the citizens in the respective cities. From a technical perspective, one of the objectives of the ICT work stream in the Triangulum project is to provide a unifying framework for integrating these diverse vertical domains into a common ecosystem- a smart city. From ICT point of view, transformation of traditional street lights to smart street lighting system will not only optimise energy use but also provide better visibility in terms of operation and maintenance of the system. Similar to some previous smart city projects such as [10], an overview of Triangulum concept is presented in Fig.1.

Previous smart city projects such as [11], [12],[13] implemented IoT as a means of connecting different aspects of the city using low-power wireless technology based on IEEE 802.15.4 standards. In those projects, endpoints such as street lamp posts were monitored through wireless communications. While the choice of wireless communication is understandable given its flexibility, from communication network architectural point of view, the pervasive nature of power lines provides the scalability required in smart street lighting. The Aspern project was also undertaken to transform Aspern; a local district in Vienna into a smart city [10]. In terms of products, new wireless offerings such as "Connected Lighting" from Greenwave and "Lighting Hub" from Philips are already in the market [2]. These products support IPv6 which is beneficial for application developers and end users. Since most communication systems and applications are IP-capable, supporting such applications on portable devices will not only increase its adoption but improve user experience through availability of graphical user interface (GUI).

Assessing the performance of a communication system in street lighting requires more than the physical or MAC layer study. Performance at these low layers dramatically changes when real application utilises the communication system to exchange information between ends of the network. Hence, it is necessary to evaluate the complete system. Given that most applications have quality of service (QoS) requirements in terms of delay, throughput, jitter or packet loss tolerance, running an application over the network seems a more appropriate way to determine the end-to-end performance of the communication system and whether it can reliably support the application in question. In concept, the smart street lights in this work employ street lamps equipped with microcontroller, PLC transceivers and suitable protocol stack that will enable them to exchange information over the network. Given that street lighting network often span several kilometers, the addition of several wireless relays or routers can undermine the cost savings initially envisaged. Therefore, the idea of this paper is to simulate street lighting system over NPLC. Using a network simulator (NS-3), we create the street light as network nodes and connect them to the base node through NPLC. Details of the communication network are provided in the Section III.

III. SIMULATION SETUP

The simulation setup employed in this study is discussed in this section. In Manchester, the Oxford road corridor has been chosen as the pilot base for this project. Oxford road is 2 miles (3.219 km) long with street lights planted at intervals. Within the smart city concept illustrated in Fig.1, street lights monitoring and control are investigated over power lines and IEEE 802.15.4 wireless networks. Tables I and II present the simulation parameters used. Generally, power line channel condition varies with time, frequency and location. In the NPLC employed in this work, impulsive noise is included as random pulses characterised by 1e-7 W, 0-2ms and 0-1ms being the power spectral density (PSD), inter-arrival time and pulse duration respectively. Technical specifications of NPLC systems as provided in different standards such IEC 61334, ITU-T G.9904 (PRIME), ITU-T G.9903 (G3-PLC) and IEEE1901.2 generally support frequencies from 3 kHz to 500 kHz but actual implementation is subject to local/regional regulations.

Various protocols such as two-way automatic communication system (TWACS), Meter&more, Homeplug command & control and open smart grid protocol (OSGP) have been developed based on specifications listed above. However, in practice, G3-PLC and PRIME are the OFDM-based NPLC technologies most widely used. Although these technologies were initially developed to meet the traffic requirements of smart grid applications, they can be adapted to other low-rate control applications such smart lighting. In this paper, we adopt part of PRIME PHY specification and investigate the performance of street lighting network powered by NPLC in 3-499kHz. While the packet size of street lighting application varies between tens and few hundreds of bytes [14] , the montoring and control messages are considered as critical traffic in this paper. Hence a packet size of 150 bytes is applied in the bi-directional communication in line with traffic characteristics of in smart grid applications [7]. The base node (controller) and lamps are IP-enabled. By generating traffic from clients to server or vice versa and returning acknowledgments, key performance metrics such as latency and congestion are measured and analysed. As TCP

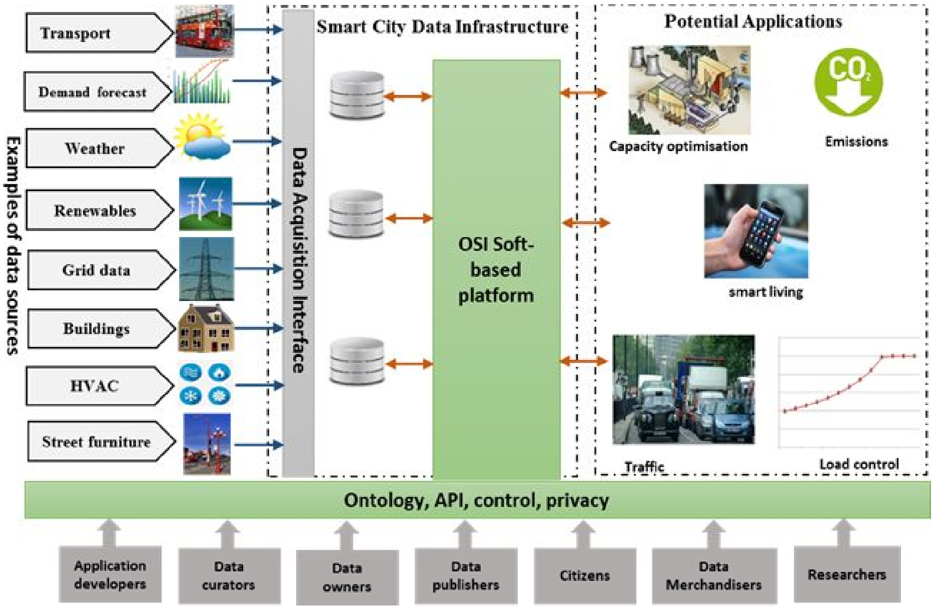


Fig. 1. Conceptual Overview of Triangulum Smart City

is a connection-oriented protocol, a three-way handshake is necessary to complete the end-to-end connection between sender and receiver.

After a connection setup or timeout, TCP (sender) initiates the slow-start algorithm during which $ssthresh$ is initially set to a large value (which translates to large window W) and recalculated at the end of each slow-start phase.

TABLE I
NPLC PARAMETERS

Mains	50 Hz
Frequency	3-499 kHz
Channel spacing	488.28125 Hz
Number of channels	1016 (510 active)
OFDM symbol time	2240 us
PHY rate	227.1209 kbps
Modulation	BPSK
Bits per symbol	1
Transmit power	2.21e-7 W
Noise model	Coloured background + Impulsive

TABLE II
LOWPAN PARAMETERS

Frequency	2.45GHz
Channel access	Unslotted CSMA
Modulation	O-QPSK
Number of channels	83
Noise model	AWGN
PHY rate	250kbps
Bits per symbol	4
Transmit power	2.21e-7 W

As data flows between the endpoints, the transmitting node periodically probes the network to estimate the congestion window W – the maximum amount of unacknowledged data that may be outstanding. W starts with a small multiple of the maximum segment size (MSS) (usually 1, 2 or 10) and is increased by 1 MSS for every acknowledgement received by the sender until another congestion or timeout is detected. At congestion if the current value of $W \geq$ last $ssthresh$, TCP enters collision avoidance (CA) phase, otherwise (if $W \leq ssthresh$) it initiates the slow-start phase.

In slow start phase, W defaults to 1 MSS while in CA state, W is reduced by half ($W = {}^{W_{max}}/_{2}$) and $ssthresh$ is set to $\frac{W_{max}}{2}$ bytes. In this phase, the transmitting node can send data at a rate γ such that ${}^{W_{max}}/_{2} \leq \gamma \leq W_{max}$. Suppose $W = \frac{W_{max}}{2}$ and the transmitting node receives acknowledgment for each segments sent, then the value of W increases by one MSS at every RTT so that each cycle is described as $\frac{W}{2}$ round trips and the delay (in seconds) is equivalent to

$$RTT * \frac{W}{2} \tag{1}$$

The CA process is analysed below[15]. Total data delivered in each cycle can be expressed as

$$\Gamma = \left(\frac{W}{2}\right)^2 + \frac{1}{2}\left(\frac{W}{2}\right)^2 = \frac{3}{8}W^2 \tag{2}$$

A lossy communication channel with a known RTT and packet loss probability ρ implies that approximately ${}^{1}/_{\rho}$ packets will be delivered in a cycle before packet loss occur in the network (assuming the losses are not related to throughput). It means that,

$$\frac{1}{\rho} = \frac{3}{8}W^2 \implies W = \sqrt{\frac{8}{3\rho}} \tag{3}$$

Hence, W represents the theoretical maximum amount of unacknowledged data that can be held in transit before TCP declares that network congestion has occured.

The throughput estimate Φ is given by

$$\Phi = \frac{DataPerCycle}{DelayPerCycle} \tag{4}$$

Using (1) to (3), we can express (4) as

$$\Phi = \frac{MSS * \frac{3}{8}W^2}{RTT * \frac{W}{2}} = \frac{{}^{MSS}/_{\rho}}{RTT\sqrt{\frac{2}{3\rho}}} = \frac{MSS}{RTT} * \frac{K}{\sqrt{\rho}} \tag{5}$$

where $K = \sqrt{3/2}$. K combines several terms that are typically constant for specific combination of TCP implementation, acknowledgement strategy and loss mechanims. The above scenario resulting in $K = \sqrt{3/2})$ is suitable for periodic losses. In typical random loss scenarios, $K < 1$. In the case of PLC, ρ must also include for loss probability due to random impulsive noise.

IV. RESULTS

In this section, the simulation results are presented and analysed. Congestion and latency are considered as key performance indicators. We begin by comparing the W of LoWPAN and narrowband power line networks. As seen in the previous section, W represents the maximum amount of data for which acknowledgement has not been received by the transmitter. Hence, in reality, it can be limited by bandwidth and receive buffer of destination device.

A. Network Congestion

In TCP, W comes handy for investigating network congestion under various load conditions as UDP does not support congestion control. The maximum value of W reflects the level of congestion between the lamps and the base node. Fig. 2. illustrates the W with single and 160 concurrent transmissions. The idea is to measure how network load impacts the congestion window using TCP.

As can be seen in Fig.2a, with a single lamp transmitting to the base node in LoWPAN, saturation occurred as 35.912KB (at 6.01199s), 18.239KB (at 8.66597s), 35.376KB (at 10.6375s), 17.704KB (at 13.8901s) and 39.088KB (at 16.6785s) while ssthresh values were 10.720KB and 5.856KB. These saturation points signify congestion either due to bandwidth or limited buffer size at the receiver. In the case of NPLC, congestion occurred at 24.656KB (at 4.59362s), 23.584KB(at 5.57881s) and 2.948KB (7.05268s) while ssthresh of 13.963KB and 1.340KB were achieved during the transmission. In order to maintain a steady flow of traffic, LoWPAN experienced multiple phases of slow-start to adapt to the prevailing network conditions, mainly determined by the link throughput and latency. NPLC maintained lower congestion window and ssthresh values, it sustained the CA (steady state) from 7.28654s till the end of the simulation as against the timeout and multiple slow-starts observed in LoWPAN. This figure shows that, although it is beneficial to keep a moderate amount of data in transit in order to maximise system throughput, the value of W must be matched with available bandwidth and delay to avoid packets drops due to network over-subscription. Figure 2b illustrates the network congestion with 160 concurrent TCP transmissions from the street lamps to the base node. The first observation is that compared with Fig.2a, less congestion can be tolerated. This is not unexpected, as the contention ratio is higher now, large W or ssthresh will result in packet losses and undue delay. Secondly, both LoWPAN and NPLC mostly maintained sstresh of 536 bytes and 1.072KB at different times during the simulation. Again these values are lower than thosee of Fig.2a due to the larger number of connections.

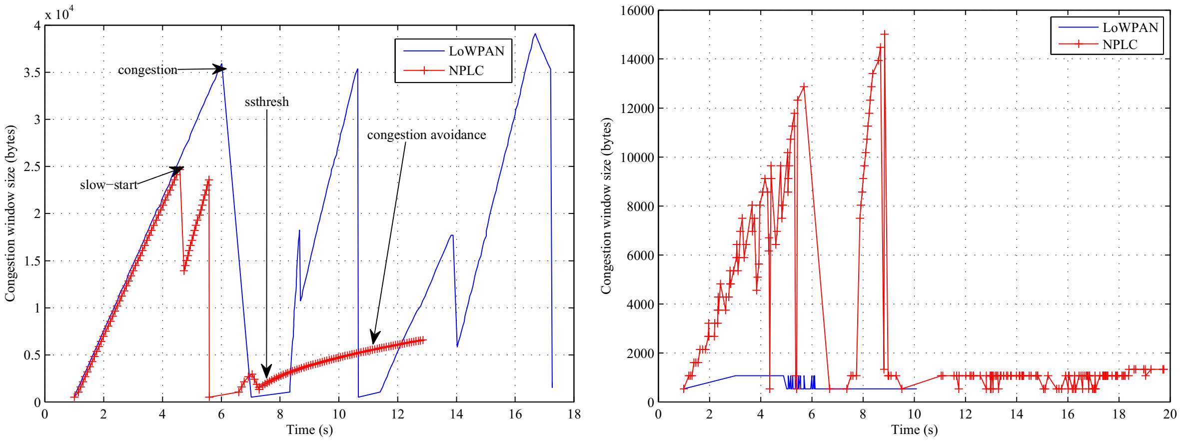
B. Unidirectional Latencies

Delay is one of the key parameter for measuring performance of any communication system. In principle, end-to-end latency comprises of queuing, transmission and propagation delays. Since packets consist of stream of bits, large packets typically translate to longer bits stream which take longer to transit the network. Hence, latency increases with frame size, until the MTU limit is reached. Packets larger than the MTU size significantly increase the end-to-end communication delay due to fragmentation and reassembly of the packet fragments. Different types of unidirectional delays between the base node and street lamps in the investigated systems are presented in Fig.3.

Fig.3a shows the changes in average downlink delay as the communication range is varied from 10 to 200 m. In this work, the street lamps are linearly positioned at 10m from one another. The downlink latency in this regard is the time taken to deliver a unicast query or control signal from the base node to each lamp. Similarly, Fig.3b shows the uplink latency as the time taken to deliver sensed or measured samples from street lamps to the base node. In both figures, the x-axis logically represents the relative distance of the lamps from the base node. It can be inferred from Figs.3a and b that with LoWPAN, only the first ten lamps successfully communicated with the base node with latency under 1.50s, all other lamps could neither transmit nor receive from the base node. Infact, in Fig.3a, the downlink latency (3.26246s) experienced by the eleventh lamp is more than twice the average latency of the preceding ten lamps and may not be suitable for certain control messages. In effect, the LoWPAN provides 50% coverage while the NPLC offered 100% coverage with maximum latency of 1.20916s.

C. Latency vs Distance

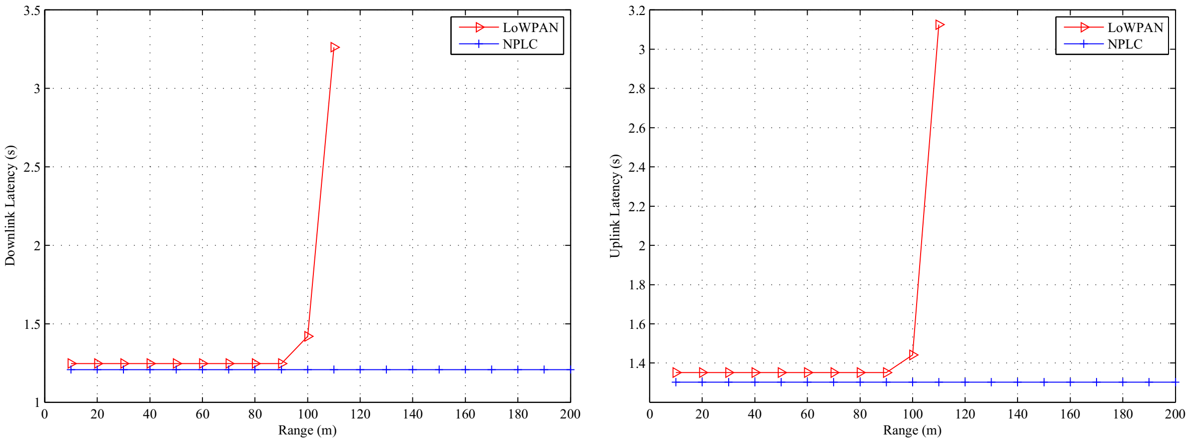
This section examines the time taken to transfer command messages from the base node to the street light using different packet sizes either to request update (such as energy consumed, operational status, total uptime, synch packet) or perform some control functions. The idea here is to simulate the monitoring/control of the street lights across the entire



(a) Congestion windows with single connection

(b) Congestion windows with 160 connections

Fig. 2. Network Congestion Windows



(a) Downlink latency from base node to street light

(b) Uplink latency from street light to base node

Fig. 3. Unidirection Latencies

Oxford road using NPLC and determine system performance. In reality, the distance between the street light varies between 9.8m and 29.4m. We applied 20m in this simulation and Fig.4 presents the variation of dowlink latency with distance and packet size.

As seen in Fig.4, transmitting small packet size reduces latency at the expense of throughput efficiency. Conversely, bigger packets are throughput-efficient as fewer packets are sent and more user data are packed into a single packet but the trade-off is higher latency. The optimum packet size therefore depends on expected outcomes in terms of application performance and whether speed is preferred at the expense of throughput or vice-versa.

Suppose an application has been installed on the lamps for monitoring and control, from Fig. 2, large TCP window means large memory for buffering. Since the power line modems are computationally constrained and expected to be inexpensive, providing large memory in the lamps is not an attractive option. Hence, in addition to low delay, small window (small buffer) is desirable. Hence, with a fixed W and a desired RTT to meet application requirements, the PLC system must be engineered to deliver at least, a throughput of Φ bytes/sec. In the simplest case (assuming every packet is acknowledged and there is no bandwidth limitation), (5) can be written as

$$\Phi = \frac{W}{RTT} \tag{6}$$

For example, based on the model used in this paper, it can be seen from Fig.4 that the street light located at 3km incurs a latency of 1.20922s to receive commands from the base node. If it is desired that the latency be reduced to 500ms, using W of 576 bytes, according to (6), theoretic minimum throughput Φ= 1.152kbps must be delivered by the power line network.

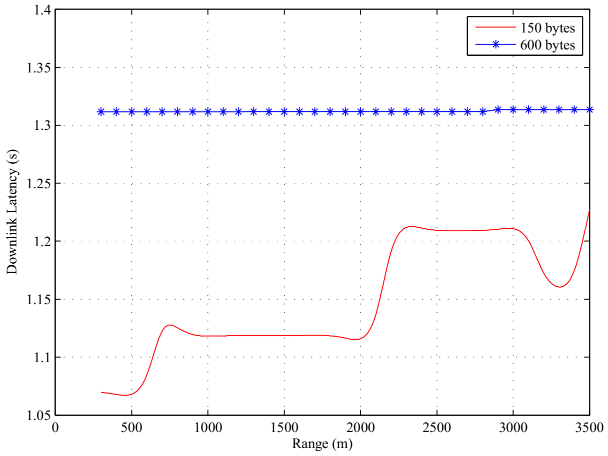


Fig. 4. Downlink latency for 3500m street light network

V. CONCLUSIONS

LoWPAN and NPLC are two major low-cost communication technologies. We have shown in this paper that low power NPLC can significantly improve performance by order of magnitude without using relays. This provides a feasible alternative where the required QoS is difficult to achieve with LoWPAN. Although the proposed low-power NPLC technique exhibited lower TCP window size with few timeouts, these can be significantly improved through the use of robust modulation and forward error control (FEC) schemes. In specific terms, while Fig. 3 indicates that, to provide network coverage for a 3.5km street light infrastructure, LoWPAN requires repeaters at every 90m to regenerate the signal, Fig.4 shows that not only can NPLC provide full coverage, optimal range of distance also exist within which the latency is flat. Depending on the street length, it follows that the network can therefore be designed to take advantage of these optimal ranges without compromising performance. Finally, Fig.4 reveals that, with NPLC, if the size of the packets travelling through the network is increased by 300%, the latency increases by 242.03ms in worst scenario and 80.28ms in the best scenario. While smaller packet sizes reduce latency, larger packets drive throughput efficiency, therefore a delicate balance is required to achieve optimal performance.

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