Energy-Efficient Street Lighting through Embedded Adaptive Intelligence

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***Abstract*—Streetlights place a heavy demand on electricity usage, providing significant financial and environmental burdens. Consequently, initiatives to reduce energy consumption have been proposed, usually by turning off or dimming the streetlight. In this paper, we propose an adaptive lighting scheme based on traffic sensing, which adaptively adjusts streetlight brightness based on current traffic conditions. The algorithm has been validated through simulation using the SUMO and OMNeT++ tools and, for two different geographical locations, the energy consumption evaluated with respect to traffic speed and volume. The simulation results presented indicate that the proposed lighting scheme can consume up to 30% less energy when compared to the state-of-the-art.**

Keywords*— energy efficient lighting, streetlight, adaptive lighting

I. INTRODUCTION

Streetlights illuminate walkways and roads during darkness to prevent crime and traffic collisions [1, 2, 3]. Studies have shown that crime in five UK cities was reduced by 38% following improvements in street lighting [4]. Streetlights also help to promote and extend socioeconomic activities, for example by allowing extended business hours [5] and gives people freedom to go out during the night. Despite the important roles that streetlights play in our daily life, sustaining their operation provides a heavy financial and environmental burden. In 2001, there were an estimated 60 million streetlights operating in the USA, which accounted for 54% of the country's outdoor energy consumption (equating to 31 TWh of electricity and 6.5 million tonnes of CO_2) [6]. In the UK, Nottinghamshire County Council reported an annual cost of £5.04M in 2011 to power their 90000 streetlights (a cost of ~£50/light) [7]. Similar financial burden has been reported by other countries, such as the Netherlands which, in 2011, spent more than €300 million powering streetlights, for which generating the electricity produced over 1.6 million tonnes of CO_2 [8].

Owing to the significant energy requirements of street lighting and its financial and environmental impact, several systems have been proposed to reduce their energy consumption. In conventional street lighting schemes, the streetlights remain lit during their operational hours (often triggered by an integrated light sensor when it gets dark). This can waste a lot of energy, especially when they are not required or full brightness is not necessary; for example during periods of low traffic volume. Part-night lighting schemes aim to reduce the energy consumption of conventional streetlights (those without the ability to dim) by turning them off at specific times and locations. Time-based dimming schemes such as Philips Chronosense and Dynadimmer [9] reduce the brightness of a streetlight to 25-50% at strategic geographic locations and at specific times where traffic flow is expected to be low [10, 7, 11], hence reducing the average energy consumed. These initiatives are aimed at reducing energy consumption and hence reduce electricity costs and carbon emissions. However, these lighting schemes are unable to uphold the perceived utility of the streetlights when their brightness is reduced. For example, reducing the brightness to 40% between 23:00 and 03:00 [9] may severely impair pedestrians' ability to navigate or avoid obstacles during these hours. Furthermore, it is difficult to predict when and where crimes or accidents are likely to take place.

Owing to this, incorporating adaptive intelligence into street lighting provides an opportunity to maintain the utility of streetlights while reducing their energy consumption and associated costs. Wireless sensor networks (WSNs) offer sensing and communication capabilities, making them ideal for many intelligent lighting control applications. Such wireless sensors can be placed at strategic locations to collect ambient information (such as brightness, user-activity, -location and -presence) to optimize both the perceived utility and the energy consumption.

Sun *et al.* [12] proposed a multi-sensor system which prolonged the operational hours of photovoltaic-powered streetlights through a reduction in average energy consumption of 40%. This reduction was obtained through the use of passive infrared (PIR) sensors and microphones which permitted the detection of humans and hence efficient and effective streetlight control. Presence detection was adopted by TU Delft [8] to create a dynamic lighting in their intelligent street lighting solution. However, with limited sensing range [13] the proposed systems are unlikely to fulfil the needs of pedestrians' perceived safety [14] and driving safety during darkness [15].

Müllner and Riener [16] adopted a Global Positioning System (GPS) and Internet enabled mobile phone to implement pedestrian-aware streetlights. Based on the received GPS signal, streetlights ahead of a pedestrian were turned on and off appropriately as they walk past. To determine and ensure correct streetlights are lit (for example to avoid lighting streetlights on parallel roads), zoning concepts were incorporated. The use of text messaging (SMS) via mobile phones was explored by Viraktamath *et al.* [17] to light streetlights on demand. The use of mobile phone in both proposed lighting schemes is a potential way of enabling better street lighting services. However, problems such as limited battery power, mobile phone network coverage and privacy (i.e. knowledge of a person's location) may prove to be major obstacles. Furthermore SMS is prone to typo errors and user interaction is not trivial in such systems, as users need to specifically request (through special commands) when they wish to switch on or off the streetlights. The limited character allowance (160 characters) in each SMS also limits its usability in the streetlight applications.

Recent work has shown considerable energy saving by turning on or off certain streetlights in a binary fashion, based on road-user proximity or location. However, operating streetlights at full brightness is often unnecessary [14]. In this paper, we propose an adaptive street lighting scheme which progressively controls streetlight brightness based upon traffic sensing. While this consideration of 'gradual streetlight dimming' has been given little consideration in previous works, the primary novelty of this paper is in the comparison of the proposed approach with state-of-the-art schemes to evaluate the effect of both traffic speed and volume on energy efficiency. The different lighting schemes are evaluated using the SUMO and OMNeT++ simulation tools, and our results indicate that our proposed lighting scheme consumes 30% less energy when compared to the state-of-the-art. Our results also show that the proposed lighting scheme achieves the best performance with low traffic volume and high travelling speed.

II. Adaptive Street Lighting using Embedded Intelligence

In this section, an adaptive lighting scheme based on traffic sensing is presented. The proposed scheme improves energy efficiency through adaptive operation enabling progressive control of streetlight brightness. This builds upon the findings of Haans *et al.* [14], where respondents claimed that they felt a better sense of safety when the streetlights were lit in a 'descending' distribution. This 'descending' distribution refers to where a streetlight immediately next to a pedestrian is operated with full brightness, and then gradually dimmed for streetlights that lay further ahead. Furthermore, it is reported that satisfactory street lighting should allow vehicle drivers to detect an object at a distance of 83 meters [15].

Fig. 1 shows the operation of the proposed scheme. First, the current light intensity, $E_v(t)$ is acquired and compared with a threshold value α. This threshold represents the light intensity when street lighting is needed. A threshold typically used is between 30 lux and 70 lux [18], depending on the application scenario. If $E_v(t) > \alpha$, daylight is assumed and hence the streetlight is turned off. Conversely, if darkness is assumed, the intelligent streetlight inspects whether or not any road users are within its sensing radius. Once road users are detected, their distance to the lamppost is computed. The streetlight brightness level is prioritized to those nearest to the lampposts, thus only the minimum distance, $\min(d)$ between the lamppost and road user is used to determine a suitable brightness. TABLE I shows the relationship between streetlight brightness and distance d used in this paper.

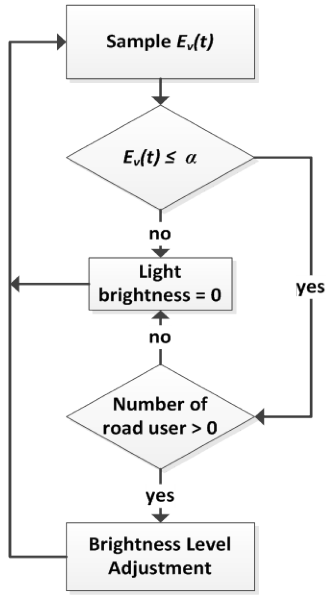


Figure 1. Algorithm for the proposed adaptive lighting scheme.

TABLE I. Relationship between object distance and brightness level in the proposed lighting scheme.

Distance from streetlight, d	Brightness Level
$0 \leq d < 20$	100%
$20 \leq d < 40$	80%
$40 \leq d < 60$	60%
$60 \leq d < 80$	40%
$80 \leq d \leq 100$	20%
$d > 100$	0%

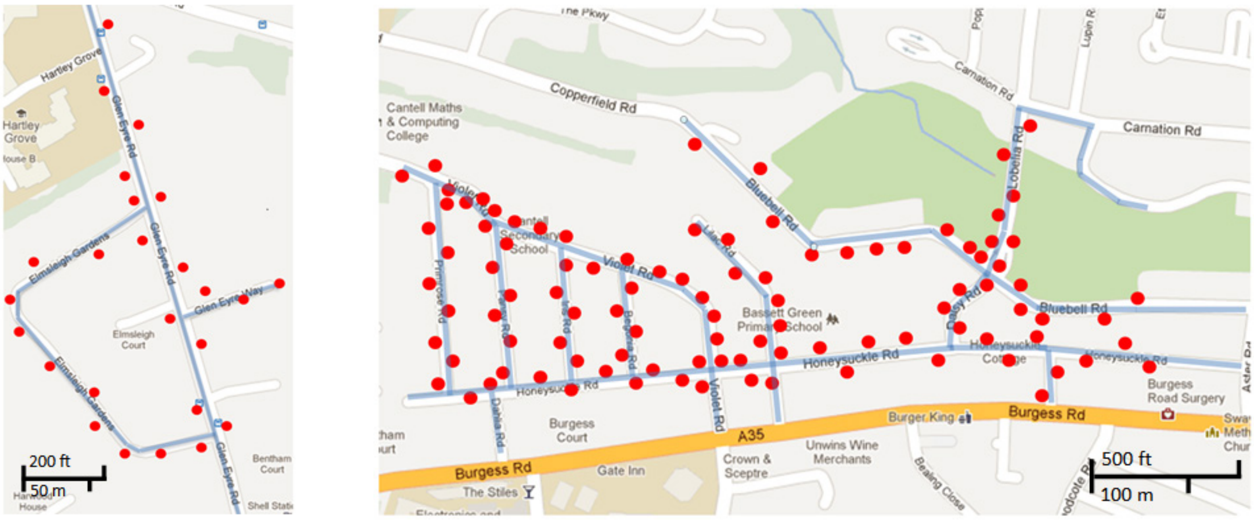
To evaluate the efficiency of different street lighting schemes, an energy model is defined (1):

$$E(N) = \sum_{n=0}^{N} P_{max}\varphi T \quad (1)$$

where $E(N)$ is the energy consumed by streetlight after N discrete time steps, φ is the dimming value or fraction of a streetlight's maximum intensity (%), P_{max} is the streetlight's maximum power rating (W) and T is the duration (s) of a single time step n. This model assumes that the streetlight's power consumption is directly proportional to its light intensity, i.e. when $\varphi = 80\%$, the streetlight's energy consumption is also reduced to 80% of P_{max}.

III. Case Study

The performance of various lighting schemes has been evaluated in terms of mean energy consumption. Three different case studies were considered in order to evaluate the performance of these schemes in different geographical locations, traffic volumes and traffic speeds.



(a) Area A

(b) Area B

Figure 2. Streetlight positions (denoted by red circles) and streets (denoted by light blue lines) involved in the case studies. [Base map was adopted from Google Maps]

A. *Simulation Parameters*

Two real geographical locations with different topologies and numbers of streetlights were adopted in our simulations. Fig. 2(a) shows the locations of the 25 streetlights in Area 'A' (covering approximately 844 m of road), while Fig. 2(b) shows the locations of 102 streetlights in Area 'B' (covering approximately 4036 m of road). The positions of individual streetlights were inferred using images from Google Street View.

Each geographical location was simulated with different traffic volumes and travelling speeds as listed in TABLE II. Traffic volumes ranging from 45 to 720 road users per hour were adopted to simulate different traffic conditions at different roads such as busy high street or quiet residential road. Different travelling speeds ranging from 1-30 m/s were adopted. Slower travelling speeds (1-2.5 m/s) were used to simulate walking pedestrians, while 5 m/s was used to simulate cyclists. Faster travelling speeds (10-30 m/s) were used to simulate moving vehicles. When realistic traffic speed is in use, each road user's speed is always restricted to the maximum allowed speed limit of the streets (e.g. speed limit of a residential street is limited to 30 miles per hour) but automatically adjusted based on traffic conditions (e.g. traffic light turning red or slow moving traffic due to congestion). Otherwise, all the road users will be assigned with same travelling speeds as listed in TABLE II.

TABLE II. TRAFFIC SPEEDS AND VOLUMES.

Traffic Volume (road users per hour)	45, 90, 180, 360, 720
Speed (m/s)	1, 1.5, 2.5, 5, 10, 15, 20, 25, 30 & realistic

To mimic realistic patterns of traffic during streetlight operation, the traffic profile shown in Fig. 3 was assumed. This profile represents a reasonable approximation of traffic volume in the locations considered.

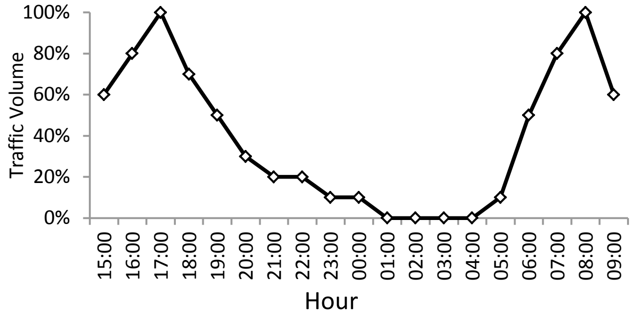


Figure 3. Traffic profile from 15:00 to 09:00.

B. *Street Lighting Schemes*

Under a conventional street lighting scheme, the simulated streetlights are always turned on at 100% brightness during the night. Under a part-night lighting scheme, all streetlights are turned on with full brightness but turned off between 00:00 and 05:30 [11]. Under time-based dimming schemes, the streetlight's brightness is reduced at preconfigured times. Two such time-based dimming schemes were simulated, namely Philips Chronosense and Dynadimmer [9]. To simulate the multi-sensor scheme proposed by Sun *et al.* [12], streetlights are always on at 40% brightness, increasing to 70% and 100% when the distance between the lamppost and road user is 20 m and 10 m respectively [13]. In our simulations, we consider the zoning scheme proposed by Müllner and Riener [16] to have a 100 m radius. As explicit details of the schemes proposed by TU Delft [8] and Viraktamath *et al.* [17] are not available, these were not included in our simulations. For all simulated schemes, we assume that the streetlights used light-emitting diodes (LEDs) in order to allow effective diming, and a module with power rating of 25W [12] was assumed.

C. Simulation Platform

All the implemented lighting schemes were simulated using a streetlight simulation platform built on top of OMNet++ and SUMO [19]. The SUMO microscopic traffic simulation environment was used as it provides atomic and detailed simulation settings on individual road users or traffic. For example, SUMO's Traffic Control Interface (TraCI), allows a road user's speed to be altered to simulate slow moving or temporary demobilized traffic to simulate an accident. We integrated OMNet++ with SUMO as previous research [20] has demonstrated the possibility of real time integration between them. In addition, its component-based architecture allows more complex and larger composite components to be assembled from reusable simple modules. This feature is essential as further extensions from this initial simulation platform are anticipated in our future work.

Fig. 4 shows the screenshots of OMNet++ and SUMO whilst simulating adaptive lighting scheme in Area 'B'. To ease the visual inspection of streetlight operations, different color codes were used to represent different brightness levels of a streetlight. For example; white in adaptive lighting scheme represents streetlight is operating at full brightness, yellow represents streetlight is operating at 80% brightness, green and bright blue represent 60% and 40% brightness respectively. When streetlight is operating at 20% brightness, navy blue is used. Black means there is no traffic and streetlight is turned off. Each scenario was simulated over a 19 hours period (assuming the longest night in the year), and repeated 10 times. The standard deviations over all simulation results were found to be less than 4%.

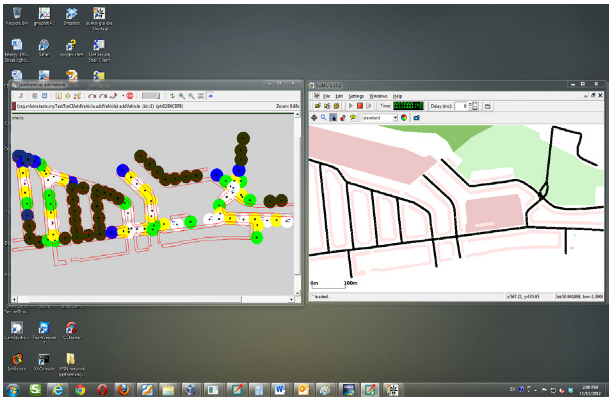


Figure 4. Screenshot of OMNet++ simulator (left) with corresponding SUMO simulator (right) when simulating the adaptive lighting screen in Area 'B'.

IV. SIMULATION RESULTS

A. Effect of Geographical Location on the Energy Consumption of Various Lighting Schemes

Fig. 5 shows the effect of geographical location on streetlight energy consumption of various lighting schemes. In this comparison, traffic volumes listed in TABLE II and realistic travelling speed were used. Based on the simulation results, adaptive, zoning and multi-sensor lighting scheme consumes considerable less energy compared to conventional, time-based and part-night lighting scheme. Compared to zoning and multi-sensor lighting scheme, the adaptive lighting scheme has outperformed these lighting schemes by consuming 30% and 72% less energy respectively.

With the same traffic volumes, both adaptive and zoning lighting scheme show approximately 40% energy reduction when operated in Area 'B'. The reduction in energy consumption in larger area (Area 'B') is due to less traffic congestion; hence the mean energy consumption is lower compared to Area 'A'. However, the energy consumption of proposed scheme in Area 'A' is almost on par compared to Area 'B' when traffic volume is doubled as shown in Fig. 6.

The performance of multi-sensor lighting scheme proposed by Sun *et al.* [12] appears to be less influenced by different geographical locations. This could be the result of its limited sensing range. Since conventional, time-based dimming, and part-night lighting scheme was not designed to interact with different traffic scenarios, their energy consumption remain consistent in both geographical locations.

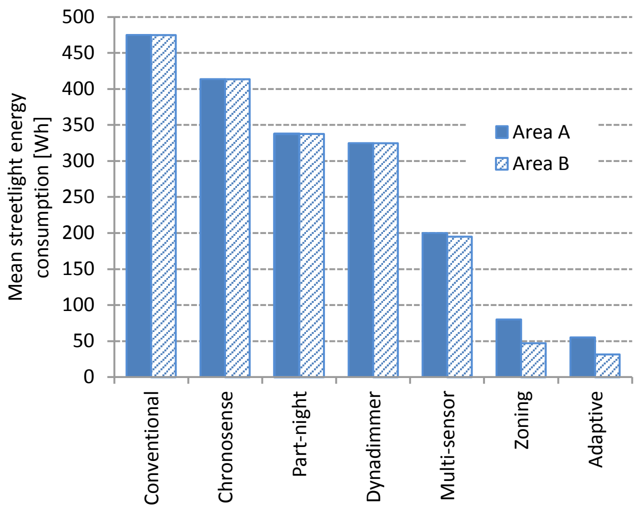


Figure 5. Effect of geographical location on the energy consumption of various lighting schemes.

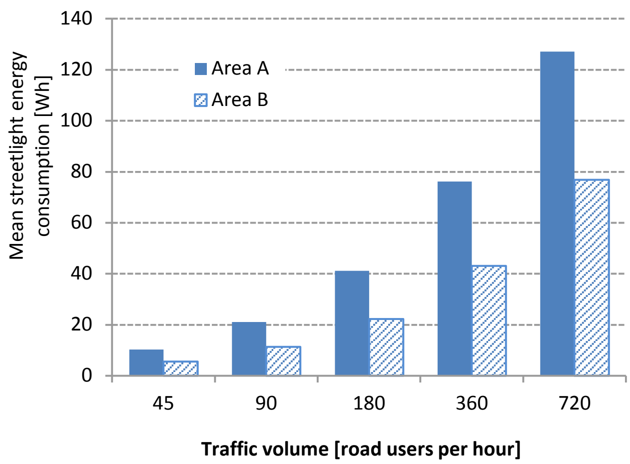


Figure 6. Effect of geographical location on the energy consumption of adaptive lighting scheme with various traffic volumes.

B. Effect of Traffic Volume on the Energy Consumption of Various Lighting Schemes

Fig. 7 shows the effect of traffic volume on the energy consumption of various lighting schemes. In this comparison, traffic volumes listed in TABLE II and realistic travelling speed were used. Based on the simulation results, the adaptive lighting scheme saves nearly 38% energy compared to zoning lighting scheme proposed by Müllner and Riener [16] under relatively low traffic volume (45 road users per hour). Under relatively high traffic volume, the performance of adaptive lighting scheme slightly decreases to 28%. Despite the slight performance drop under high traffic volume, the adaptive lighting scheme still outperforms by demonstrating 32% less energy consumption, on average, compared to zoning lighting scheme. Compared to others, 51% minimum energy saving can be achieved during high traffic volume and 96% during low traffic volume.

In all simulation scenarios, only the adaptive and zoning lighting scheme exhibits observable changes in energy consumption with increasing traffic volume. Both of these lighting schemes show an increase in energy consumption as more streetlights are turned on when traffic volume is increased. This is because increased traffic volume results in a near-continuous stream of traffic within the detection zone of each streetlight; hence the time each streetlight spends active is also prolonged. Furthermore, the streetlights are mostly at full-brightness, thus further increasing the energy consumption of these lighting schemes. This trend starts to saturate when traffic volume is increased to 720 road users per hour. Further saturation is expected with the increment of traffic volume from 720 road users per hour. The energy consumption of the adaptive lighting scheme remains lower, particularly during midnight and early morning when the traffic volume is low. Owing to the limited operation distance, multi-sensor lighting scheme shows rather consistent energy consumption across different traffic volumes.

C. Effect of Travelling Speed on the Energy Consumption of Various Lighting Schemes

The objective of this comparison is to evaluate the proposed scheme's performance under different travelling speeds. In this comparison, travelling speeds ranging from 1 m/s to 30 m/s were used. Each travelling speed was simulated with different traffic volumes as listed in TABLE II. Fig. 8 shows the effect of travelling speed on the energy consumption of various lighting schemes. Based on the simulation results, slower travelling speeds exhibit higher energy consumption for adaptive, zoning and multi-sensor lighting scheme. A rapid reduction in energy consumption is observed when travelling speed is increased from 1 m/s to 5 m/s, but slowly saturated with higher travelling speed (from 10 m/s to 30 m/s). This trend is caused by a shorter average travel time per route when road users travel with higher speeds. Thus, average streetlight operation time is reduced and total energy consumed is also decreased. On average, the adaptive lighting scheme uses 24% less energy compared to zoning lighting scheme. Compared to multi-sensor scheme, a maximum saving of 89% is achieved with travelling speed of 30 m/s.

Based on the simulation results, the performance of the adaptive and zoning lighting scheme is highly influenced by increasing travelling speed compared to multi-sensor lighting scheme. Both lighting schemes show similar trends in energy reduction with increasing travelling speed. The performance of these schemes is almost identical (i.e. a difference of 15Wh) when evaluated with travelling speeds of 30 m/s. Although it was designed to operate on traffic sensing approach, the multi-sensor lighting scheme shows rather consistent energy consumption when travelling speed increased.

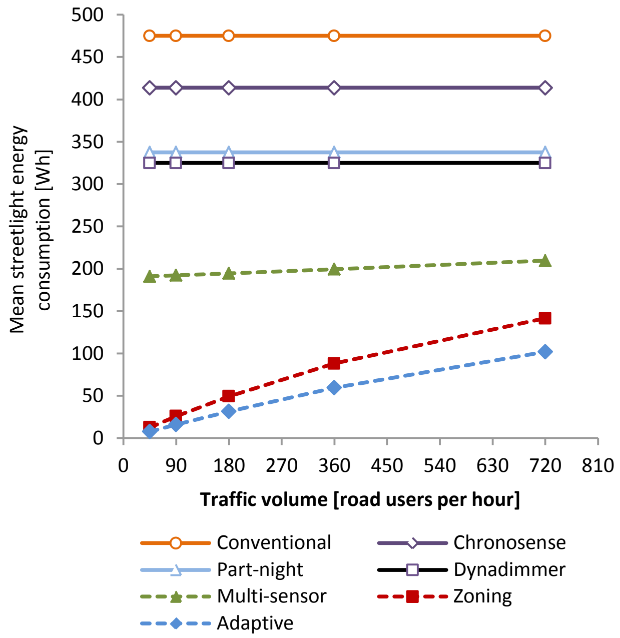


Figure 7. Effect of traffic volume on the energy consumption of various lighting schemes.

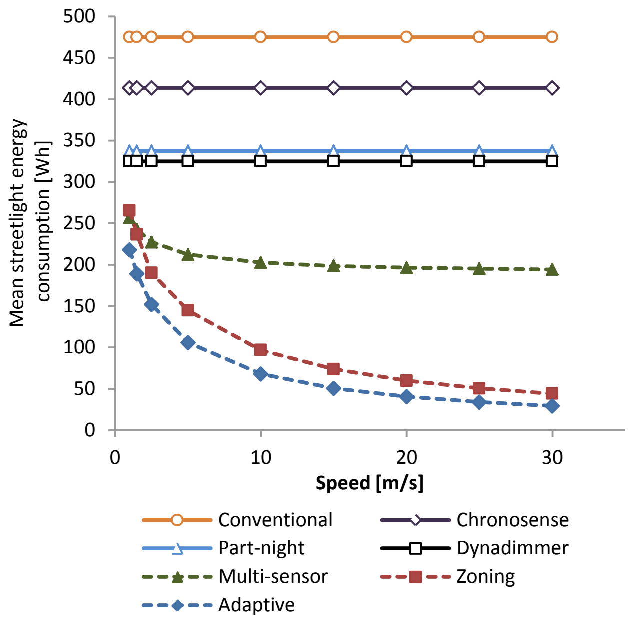


Figure 8. Effect of travelling speed on the energy consumption of various lighting schemes.

V. CONCLUSIONS

Street lighting is an important pervasive utility but it places a heavy demand both financially and environmentally. Recent work has shown considerable improvement on streetlight energy consumption but operating streetlights at full brightness is often unnecessary. In this paper, an adaptive street lighting scheme based on traffic sensing is proposed to progressively control the streetlight brightness level. The energy consumption of proposed lighting scheme has been evaluated through simulation, using SUMO and OMNet++ tools.

Three simulation parameters, namely traffic volume, travelling speed and real geographical location of streetlights have been used to evaluate the performance of various lighting schemes. In addition, a traffic profile represents a reasonable approximation of traffic volume is also considered in our performance evaluation. The results indicate that the proposed scheme consumes considerable less energy compared to state-of-the-art in all scenarios. On average the proposed scheme consumes 30% less energy compared to state-of-the-art and 90% less energy compared to conventional scheme. The results also indicate that travelling speed, traffic volume and geographical location have different influences on the energy consumption of the proposed scheme. When travelling speed increases, the energy consumption of proposed scheme is reduced. However the performance soon been optimized with increasing travelling speed and almost identical compared to state-of-the-art with a difference of 15 Wh. The proposed scheme exhibits higher energy consumption when traffic volume is increased. This performance drop is the result of prolonged streetlight operation time. Owing to the traffic congestion built up in the smaller area and traffic volume is increased at times; the proposed scheme consumes approximately 40% more energy in smaller area compared to larger area. To conclude, the proposed scheme shows better performance with low traffic volume and high traveling speed.

Our proposed adaptive lighting scheme exhibits potential energy saving compared to state-of-the-art, however further research challenges need to be addressed to realize its full potential. . One example of this is the addition of intelligence into the system, where streetlights can communicate with each other to indicate the presence of an incoming object. To enable this, low-latency networking is required to relay such time-sensitive information through the network.

REFERENCES

[1] R. A. Hargroves, "Road lighting," Physical Science, Measurement and Instrumentation, Management and Education - Reviews, IEE Proceedings A, vol. 130, no. 8, pp. 420 - 441, Nov. 1983.

[2] D. Herbert and N. Davidson, "Modifying the built environment: the impact of improved street lighting," Geoforum, vol. 25, no. 3, pp. 339 - 350, 1994.

[3] K. Painter, "The influence of street lighting improvements on crime, fear and pedestrian street use, after dark," Landscape and Urban Planning, vol. 35, no. 2 - 3, pp. 193 - 201, 1996.

[4] B. C. Welsh and D. P. Farrington, "Effects of improved street lighting on crime," Campbell Systematic Reviews.

[5] S. Hiranvarodom, "A comparative analysis of photovoltaic street lighting systems installed in Thailand," in Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on, 18 -18 May 2003.

[6] Navigant Consulting Inc. and XENERGY Inc., "Volume I: National Lighting Inventory and Energy Consumption Estimate," Sept. 2002.

[7] Nottinghamshire County Council, "Street Lighting Energy Saving - Nottinghamshire County Council," 2012. [Online]. Available: http://www3.nottinghamshire.gov.uk/travelling/roads/road-design-and-maintenance/street-lighting/energy-saving-project/. [Accessed 19 Mar. 2012].

[8] Delft University of Technology, "Intelligent street lighting at TU Delft saves up to 80% on energy," 11 Jul. 2011. [Online]. Available: http://home.tudelft.nl/en/current/latest-news/article/detail/intelligente-straatverlichting-tu-delft-kan-tot-80-energie-besparen/. [Accessed 19 Mar. 2012].

[9] Koninklijke Philips Electronics N. V. , "Different ways: The Dynadimmer and the Chronosense," 2010. [Online]. Available: http://www.lighting.philips.co.uk/subsites/oem/product_pages/dynadimmer_overview.wpd. [Accessed 21 05 2012].

[10] A. Matheson, "Reducing Energy Consumption - Street Lighting," 2008.

[11] Somerset County Council, "Somerset County Council: Reduction of street lighting in Somerset," 2011. [Online]. Available: http://www.somerset.gov.uk/irj/public/council/initiatives/initiative?rid=/guid/30afb148-555c-2e10-10be-ae0d39444537. [Accessed 19 Mar. 2012].

[12] J. H. Sun, J. F. Su, G. S. Zhang, Y. Li and C. Zhao, "An Energy-Saving Control Method Based on Multi-sensor System for Solar Street Lamp," in Digital Manufacturing and Automation (ICDMA), 2010 International Conference on, 18-20 Dec. 2010.

[13] Y. Wu, C. Shi and W. Yang, "Study of acquisition streetlights background signal by multi-sensor array," in Control Automation and Systems (ICCAS), 2010 International Conference on, 27-30 Oct. 2010.

[14] A. Haans and Y. A. W. de Kort, "Light distribution in dynamic street lighting: Two experimental studies on its effects on perceived safety, prospect, concealment, and escape," Journal of Environmental Psychology, 2012.

[15] A. Mayeur, R. Brémond and J. M. C. Bastien, "Effects of the viewing context on target detection. Implications for road lighting design," Applied Ergonomics, vol. 41, no. 3, pp. 461 - 468, 3 May 2010.

[16] R. Müllner and A. Riener, "An energy efficient pedestrian aware Smart Street Lighting system," International Journal of Pervasive Computing and Communication, vol. 7, no. 2, pp. 147-161, 2011.

[17] S. V. Viraktamath and G. V. Attimarad, "Power saving mechanism for street lights using wireless communication," in Signal Processing, Communication, Computing and Networking Technologies (ICSCCN), 2011 International Conference on, 21-22 July 2011.

[18] Eterna, NEMA Socket Electronic Photocell/Kit - Safety and Installation Instructions.

[19] M. Behrisch, L. Bieker, J. Erdmann and D. Krajzewicz, "SUMO - Simulation of Urban MObility: An Overview," in SIMUL 2011, The Third International Conference on Advances in System Simulation, 2011.

[20] C. Sommer, Z. Yao, R. German and F. Dressler, "Simulating the influence of IVC on road traffic using bidirectionally coupled simulators," in INFOCOM Workshops 2008, IEEE, 13-18 Apr. 2008.