Energy-Efficient Traffic-Aware Street Lighting Using Autonomous Networked Sensors

by

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Thesis for the degree of Doctor of Philosophy

January 2016
Street lighting is a ubiquitous utility. It does not only illuminate the streets during the night but also helps to prevent crime and traffic collisions. However, to sustain its operation is a heavy burden both financially and environmentally. Because of this, several initiatives have been proposed to reduce its energy consumption. However, most initiatives are mainly aimed at energy conservation and have given little consideration about the usefulness of street lighting.

A Streetlight Usefulness Model, an evaluation metric used to measure the usefulness of street lighting to road users, is proposed. Using StreetlightSim, a real-time co-simulation environment developed as part of this research, the energy efficiency and usefulness of six existing street lighting schemes have been evaluated. Their performances were used as baseline results which later justified the proposal of Traffic-aware Lighting Scheme Management Network (TALiSMaN). Simulation results show that TALiSMaN can achieve comparable or improved usefulness (> 90%) to existing schemes, while consuming as little as 1 – 55% of the energy required by existing schemes.

To consider the limitation of ‘off-grid’ streetlights – those powered locally by renewable energy, TALiSMaN has been enhanced with an energy demand predictor to ensure that a limited energy budget can be used fairly throughout the whole night. This enhanced scheme is known as TALiSMaN-Green. Combined with knowledge of the amount of energy stored, and predicting sunrise times, TALiSMaN-Green modulates the lighting levels requested by TALiSMaN if the energy stored is predicted to be insufficient for an entire night. The results show that this scheme extends the operational lifetime of solar-powered streetlights from 2 to 16 hours. Evaluated with real traffic flow and solar readings, TALiSMaN-Green can maintain streetlight usefulness at 60 – 80% (mean = 73% with standard deviation of 9%). In comparison, the streetlight usefulness of TALiSMaN was reduced to below 30%.
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Declaration of Authorship

I, Sei Ping Lau, declare that the thesis entitled *Energy-Efficient Traffic-Aware Street Lighting Using Autonomous Networked Sensors* and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as listed in Section 1.4

Signed:.......................................................................................................................

Date:..........................................................................................................................


Date:..........................................................................................................................
Acknowledgements

Undertaking this doctoral journey has been a life-changing experience and it would not have been achievable without the support that I have received from many people.

First and foremost, my sincere gratitude to my supervisory team, Geoff Merrett, Alex Weddell, and Prof Neil White for their supervision, encouragement and support. It was an honour to be able to work with them. I am especially grateful to Geoff and Alex for their constant feedback, having confidence in my work and inspiring me to achieve more than I could imagine.

I gratefully acknowledge the Ministry of Education, Malaysia and Universiti Malaysia Sarawak for granting me the opportunity to further my studies at the University of Southampton. Also, I am thankful for the research facilities provided by the School of Electronics and Computer Science, and for the use of the IRIDIS High Performance Computer Facility throughout my studies at Southampton.

My thanks also go to my friends in the ESS group, especially Teng Jiang and Huma Zia, who were always there for discussion and advice. Outside of my studies, I am especially lucky to have Chong Eng Tan, and my cousin Marlene Lee and her family for bringing joyful festival seasons to my family.

Finally, thanks to my parents for giving me strength and support over the past four years. Special acknowledgement must go to my wife, Mei Ching for being extremely patient and accommodating during my studies. Lastly, thanks to my two wonderful children, Denise and Ethan who are always putting a smile on my face.

With the oversight of my supervisory team, this thesis has been proofread and edited by Jane L. Watson of JLW Proofreading Services. However, no of intellectual content were made as a result from this service.
Abbreviations

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<td>AADF</td>
<td>Annual average daily traffic flow</td>
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<tr>
<td>AI</td>
<td>Artificial intelligence</td>
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<td>AODV</td>
<td>Ad hoc on demand distance vector algorithm</td>
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<td>ARIMA</td>
<td>Auto-regressive integrated moving average</td>
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<td>CAP</td>
<td>Contention access period</td>
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<td>CCT</td>
<td>Correlated colour temperature</td>
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<tr>
<td>CDF</td>
<td>Coordinated depth forwarding protocol</td>
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<tr>
<td>CEN</td>
<td>European Committee for Standardization</td>
</tr>
<tr>
<td>CFP</td>
<td>Contention free period</td>
</tr>
<tr>
<td>CIE</td>
<td>International Commission on Illumination</td>
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<tr>
<td>CRI</td>
<td>Colour rendering index (also known as $R_a$)</td>
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<tr>
<td>CSMA-CA</td>
<td>Carrier sense multiple accesses with collision avoidance</td>
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<td>DfT</td>
<td>Department for Transport, UK</td>
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<td>DoW</td>
<td>Day-of-Week data aggregation strategy</td>
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<td>EWMA</td>
<td>Exponentially weighted moving average</td>
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<td>FB</td>
<td>IEC 61499 Function block</td>
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<tr>
<td>FC</td>
<td>Fuel cell</td>
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<tr>
<td>FWMA</td>
<td>Fixed-weighted moving average</td>
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<tr>
<td>GGPSR</td>
<td>Geocast greedy perimeter stateless routing protocol</td>
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<tr>
<td>GPS</td>
<td>Global positioning system</td>
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<tr>
<td>GPRS</td>
<td>General packet radio service</td>
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<tr>
<td>GPSR</td>
<td>Greedy perimeter stateless routing</td>
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<td>GTS</td>
<td>Guaranteed time slot</td>
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<td>HPS</td>
<td>High pressure sodium</td>
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<td>IQR</td>
<td>Interquartile range</td>
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<td>JiST</td>
<td>Java in simulation time</td>
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<td>LED</td>
<td>Light emitting diode</td>
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<tr>
<td>MAC</td>
<td>Media access control layer</td>
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<tr>
<td>MAE</td>
<td>Mean absolute error</td>
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<tr>
<td>MOVE</td>
<td>Mobility model generator for vehicular network</td>
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<tr>
<td>NED</td>
<td>Network description language</td>
</tr>
<tr>
<td>ns</td>
<td>Network simulator</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>OMNeT++</td>
<td>Objective modular network testbed</td>
</tr>
<tr>
<td>OTcl</td>
<td>Object tool command language</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical layer</td>
</tr>
<tr>
<td>PIR</td>
<td>Passive infrared</td>
</tr>
<tr>
<td>PKU-STRAW-L</td>
<td>Peking University street random waypoint for Lamp</td>
</tr>
<tr>
<td>PLC</td>
<td>Power line communication</td>
</tr>
<tr>
<td>PDD</td>
<td>Previous-D-Days data aggregation strategy</td>
</tr>
<tr>
<td>RREQ</td>
<td>Route request message</td>
</tr>
<tr>
<td>RT</td>
<td>Routing table</td>
</tr>
<tr>
<td>SMA</td>
<td>Simple moving average</td>
</tr>
<tr>
<td>SMS</td>
<td>Short message service</td>
</tr>
<tr>
<td>STRAW</td>
<td>Street random waypoint mobility model</td>
</tr>
<tr>
<td>SUMO</td>
<td>Simulation of urban mobility</td>
</tr>
<tr>
<td>SWANS</td>
<td>Scalable wireless ad hoc network simulation</td>
</tr>
<tr>
<td>TALiSMaN</td>
<td>Traffic-aware lighting scheme management network</td>
</tr>
<tr>
<td>TIGER</td>
<td>Topologically Integrated Geographic Encoding and Referencing</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission control protocol</td>
</tr>
<tr>
<td>TraCI</td>
<td>Traffic control interface</td>
</tr>
<tr>
<td>TraNS</td>
<td>Traffic and network simulation environment</td>
</tr>
<tr>
<td>VANET</td>
<td>Vehicular ad hoc network</td>
</tr>
<tr>
<td>Veins</td>
<td>Vehicles in network simulation</td>
</tr>
<tr>
<td>WDE</td>
<td>Weekday-Weekend data aggregation strategy</td>
</tr>
<tr>
<td>WSNs</td>
<td>Wireless sensor networks</td>
</tr>
</tbody>
</table>
Nomenclature

$\alpha_{\theta}$  Weighting factor of road traffic volume by days of week
$\alpha_{\text{ped}}$  Weighting factor of time spent by a pedestrian looking at the footpath
$\alpha_{\text{cond}}$  Conditioning factor to the requested lighting level, $\varphi$
$\alpha_{\text{exp}}$  Weighting factor of exponentially weighted moving average
$\alpha_{\text{fix}}$  Weighting factor of fixed-weighted moving average
$\alpha_{\text{sel}}$  Coefficient of predictor selection metric
$\alpha_{\text{solar}}$  Random solar noise factor
$\gamma$  Ratio of streetlight lighting level at $x$ metres from a road user to the minimum required lighting level designated for the road where the road user is travelling on
$\Gamma$  Total number of simulated road users per day
$\varphi_{\text{mot}}$  Lighting level of a streetlight for detected motorist (%) $\varphi_{\text{ped}}$  Lighting level of a streetlight for detected pedestrian (%) $\Delta_{\text{ped}}$  Additional pedestrian traffic composition (%) $d_{\text{approx}}$  Approximate relative distance from a streetlight to the detected pedestrian (m) $d_{\text{avg}}$  Average distance to the next adjacent streetlight $d_{det}$  Euclidean distance to the nearest sensor node that detects the road user (m) $d_{\text{rad}}$  Maximum detection range of a road-user sensor (m) $E_h$  Lighting level on a horizontal plate (lx) $E_{\text{cap}}$  Capacity of an energy storage device (Wh) $E_{\text{cons}}$  Energy consumed by a streetlight (Wh) $E'_{\text{demand}}$  Expected energy demand of a streetlight until sunrise (Wh) $E_{\text{harvested}}$  Harvested solar energy (Wh) $E_{\text{stored}}$  Energy stored in a battery (Wh) $I_{\text{sel}}$  Predictor selection metric $P_{\text{max}}$  Maximum power rating (W) $P_{\text{solar}}$  Observed solar power ($\text{W/m}^2$) $P_{\text{efficiency}}$  Solar power conversion efficiency (%) $P_{\text{size}}$  Size ratio of a solar cell
\( R_a \)  
Colour rendering index

\( R_{MAE} \)  
Ratio of MAE to average daily energy demand of TALiSMaN at specific traffic volume

\( R_{resources} \)  
Ratio of computing resources required by a predictor to available computing resources of a wireless sensor node

\( T_{BO} \)  
Random number of back-off periods

\( T_{CCA} \)  
Clear channel assessment period

\( t_{exp} \)  
Expiration time of the state delay counter (s)

\( t_{rise} \)  
Actual sunrise time

\( t_{rise}^\prime \)  
Estimated sunrise time

\( U_{mot} \)  
Streetlight usefulness for motorist

\( U_{ped} \)  
Streetlight usefulness for pedestrian

\( U_{ped(avoid)} \)  
Streetlight usefulness for pedestrian in obstacle detection, navigation and facial recognition

\( U_{ped(prospect)} \)  
Streetlight usefulness for pedestrian’s perceived safety

\( V_{mot} \)  
Annual average daily traffic flow for vehicular traffic (vehicles per hour)

\( V_{comb} \)  
Annual average daily traffic flow with both vehicular and pedestrian traffic (road users per hour)

\( V_{\theta} \)  
Average daily, or average weekday and weekend traffic volumes

\( V_{avg} \)  
Average weekly traffic volume

\( z \)  
Ratio of the lighting level at location \( x \) metres from a road user at time \( t \) to the lighting level required at the illumination zone where location \( x \) is located

\( Z_{ped} \)  
Illumination zone of streetlight according to the relative distance to detected pedestrian
Chapter 1

Introduction

Street lighting is a ubiquitous utility that can be found in most urban areas, and is used for a number of different purposes. As street lighting improves visibility during the hours of darkness, crime detection becomes easier and the presence of authority, such as the police, becomes more visible [1]. As a result, potential offenders are likely to desist from committing crimes. For example, crimes in Dover, Bristol, Birmingham, Dudley and Stoke-on-Trent, UK have been reduced by 38% by having adequate street lighting [2]. Fear of crime discourages many people from travelling at night; one of the causes of this is dark or poorly lit roads. As a result, improved street lighting encourages more socio-economic activities during the night [3,4]. Consequently, this promotes greater road use after dark. Street lighting also has a prominent role in reducing the risk of accidents after dark by reducing traffic collisions by over 50% [5]. Compared to during daylight hours, the risk of an accident involving pedestrians on a lit road increases by 141%. For unlit roads, however, this figure rises by 360%.

Although the benefits of street lighting are clear, sustaining its operation has become a concerning issue to local governments, both financially and environmentally. Globally, there are over 90 million streetlights consuming approximately 114 TWh of energy annually [6]. This represented about 33% of the UK’s annual electricity consumption in 2012 [7], equivalent to an emission of 52 million tonnes of CO$_2$ (based on the 2012 power conversion factor of 0.46 kg/kWh [8]). With rising energy prices and rapid urbanisation, the cost of street lighting is expected to grow as the number of streetlights is predicted to increase by over 300% by 2025 [9]. For example, in 2011, Nottinghamshire County Council in the UK spent more than £5m on the energy cost for street lighting, representing a 360% increment compared to 2005 [10].

Efforts to reduce the energy cost of street lighting, and hence reduce carbon emissions, have focussed on two aspects: replacement of each streetlight’s luminaire, and its control mechanism. The replacement of end-of-life streetlights with newer and more energy-efficient luminaires has delivered significant energy savings. For example, in Thailand,
a 25 – 30% energy saving was achieved with a new High Pressure Sodium (HPS)-based luminaire [11]. Recent developments in Light-Emitting Diode (LED)-based luminaires have resulted in a further 25% power reduction, and have virtually no disadvantage/deterioration over being regularly switched, and deliver light instantly when switched on [12,13].

Conventionally the control, or ‘switching mechanism’ of a streetlight, is realised by a clock with a predefined schedule or an integrated light sensor which indicates when the surrounding environment becomes dark. Once switched on, streetlights remain lit continually throughout the night. However, this conventional or ‘always-on’ lighting scheme can result in energy wastage, especially when roads are only intermittently used and lighting at full brightness is not necessary. Examples of this include the early hours of the morning, when very low traffic volumes are expected. Owing to this, 75% of local councils in the UK have selectively dimmed or completely turned off streetlights during late and early hours when low traffic volumes are expected [14]. Warwickshire County Council in the UK anticipates an annual saving of £0.5m and about a 25% reduction in CO₂ emissions caused by street lighting, if operating their streetlights on this basis [15].

In considering the energy and CO₂ emissions that can be saved via dimming, many have adopted communication and sensing technologies to improve the control of light levels. Remote-controlled street lighting offers significant prospects for saving energy as continual adjustment of light levels is possible [16–18]. With this approach, an operator at a remote control centre performs the necessary management and regulation of streetlight operation, such as dimming for energy conservation and health monitoring of the streetlights. In some cases, light levels are autonomously adjusted based on ambient information, such as weather and traffic conditions, collected by a local sensor array [19,20]. Most of the proposed remote- and sensor-controlled street lighting approaches adopt wireless communication networks to establish a communication link between a remote control centre and an individual streetlight. Instead of sensing the traffic, Müllner and Riener [21] utilised Global Positioning System (GPS) and Internet-enabled smartphones to track the precise location of pedestrians, and hence only streetlights within a defined radius of them are turned on. Recently, the adoption of artificial intelligence (AI) techniques such as agent-based systems [18,22], fuzzy logic [23] and artificial neural networks [24] in street lighting have also been reported. The main advantage of adopting AI is to enable the self-management of the streetlights with the ability to adapt with minimum human intervention.

The mains power grid is the typical energy source used for street lighting. Although energy demand for street lighting can be reduced via dimming, a significant amount of energy is still required. Access to the mains power grid and long-range communication network is limited in some areas. There has recently been increased interest in the use of renewable or green energy sources to provide their power [25]. These ‘off-grid’ streetlights, or streetlights which are powered locally from renewable energy, are most useful in remote