Road and street smart lighting control systems as a new application area of the hot-potato protocol

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This paper presents the new application area of the hot-potato routing protocol, which is a "last-mile" communication network for controlling systems of road and street lighting. Four variants of the hot-potato protocol are analyzed with use of the graph theory. For the assessment of the traffic parameters the ETX parameter is used in relation to the length of the shortest path. Proposed methods are independent of the media type and can be implemented either in wireless or PLC.

KEYWORDS: smart lighting, smart grid, lighting control network, road lighting, street lighting, PLC, WSN

1. Introduction

There are many reasons why an individual light point controlling is more efficient than a light line controlling. The main advantage of the individual light point controlling is of course economical efficiency, mainly within the meaning of energy saving as well as in terms of the life of lighting installation. Taking into account that for some modern light sources, e.g. LED, the individual controlling is the only way to dim them. There are, of course some disadvantage of the individual light point controlling such as the necessity for employing a "last-mile" communications system. Even though the "last-mile" communications systems are rather not complicated they generate quite large investments costs because of their quantity. This situation is very similar to the communications systems used in automatic meter reading (AMR) of electricity consumption meters.

The hardware solutions of "last-mile" communications systems for smart metering are fairly similar to smart lighting ones, but the system solution, i.e. communications protocols and topology control implementations, are significantly

521

different. This difference in communications protocols types is a result of a method of operating in smart metering once run "last-mile" network executes till the blackout, whilst in smart lighting "last-mile" network is run at least once a day. The difference in topology control approach is due to the different topological forms created by the watt-hour-meters and lamps. In smart metering, typically, the network topology consists of a number of trees [1], which is very often treated as a mesh network whilst the most often topology created by the street or road lamps is the link or a set of links. A similar situation occurs with the wireless sensor networks (WSN), where except the system differences, additionally energy issues exist and dedicated communications protocols must be involved to reduce this problem [2].

Until now mainly differences in the system solution have been discussed but there are also two features that allow us to have a similar approach to the communications scheme namely connectivity and coverage. Connectivity means the ability of data transmission between all nodes of the network considering that it is possible to transmit information between adjacent nodes, whereas coverage means capability of gathering information from the assigned area.

Given the characteristics of the communication for smart lighting, the hot-potato protocol [3] is seemed to be very useful for light controlling mostly because it is heuristic. One of the hot-potato protocol doctrines is to achieve real-time operation to respond to changes in network status caused by changeable communications conditions and very often turning the nodes on and off. Other important reasons, from the point of view of the considered problems, include: self configuration and dynamic adaptation, fault-tolerant and at the end – small memory requirements which is particularly important in smart grid communication systems, where memory deficit always exists because of information encryption needs [4].

The aim of this paper is to propose a method of adaptation of the hot-potato protocol to smart lighting specificity as well as to propose a method of traffic analysis in the context of connectivity and coverage. The presented method is adequate for all types of networks, in which to enlarge the range a multi-hop technique is used. The study considered two transmission technologies: wireless in ISM band and wired narrowband PLC (Power Line Communication), which uses the same wires both for power supplying as well as data transmission. All considerations apply to the individual light point controlling for all the types of light sources used in road and street lighting.

2. Proposed method of analysis

The proposed analysis method is a combination of methods based on graph theory and computer simulation. Computer simulation was used only if the problem could not be solved by analytical methods e.g. studying the behavior of the hot-potato protocol with many variants but never in the area of the description of low voltage (LV) and wireless network topologies.

Graph can describe the network, including LV network used for street and road lamps controlling and supplying. In turn, the graph can be described by its adjacency matrix [5]. The adjacency matrix [*AM*] is a square matrix of *w* x *w* dimension (where *w* denotes the number of nodes forming this network) which defines mutual incidence of the graph nodes. The elements of the matrix are assigned as am_{ij} and can take values from set {0, 1}, so that if $am_{ij} = 1$, there is a connection between nodes w_i and w_j whereas if $am_{ij} = 0$, there is no connection between these nodes.

The state of the connections between the two nodes *i* and *j* is described by two elements: am_{ij} and am_{ji} what give us four combinations: 00, 01, 10 and 11. The combination of 00 tells us that nodes are out of range or are not included in routing, whilst the combination of 11 means a bidirectional connection between two nodes, 01 and 10 mean unidirectional connections. A well-known feature of the [*AM*] is that elements of $[AM]^h$ matrix determine the number of routes with length h – with h hops. Knowing the fact that the hot-potato protocol never uses the multi-path technique information about number of routs is not useful but taking in to account that the hot-potato protocol always uses the multi-hop technique it would be useful to know the probability of selection the route of given length (number of hops).

The proposed method is a modification of the [*AM*] matrix, which depends on describing the state of the connections between the two nodes *i* and *j* by two elements: amp_{ij} and amp_{ji} which may have value from 0 to 1. Modified matrix will be assigned as [*AMp*] and its amp_{ij} element is the probability that information will be forwarded from *i* node via *j* node. Determination of probabilities for each node is the essence of the proposed method. Four methods for determining the probabilities are shown in Figure 1.
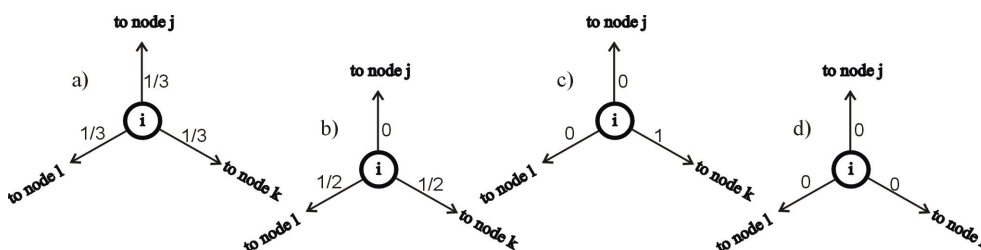

Fig. 1. Example of four methods for determining the probabilities: a) forwarding via any of adjacent nodes is equally probable, b) forwarding via j-node is excluded, c) forwarding via one, determinate node (k-node), d) forwarding discontinued

Example a) represents situation when a transferring node cannot determinate any rule of routing– the probability value is equal to $1/d$ where *d* is the degree of the node.

Example b) shows situation when a transferring node excluded one way – other ways are equally probable and have value of $1/(d\text{-}1)$. In practice, such a situation takes place when a transferring node knows address of the node from

which information has been received. Taking into account that both for PLC and wireless transmission shared medium is used the overhead of frame must be equipped not only with destination, source and transferring addresses but also with predecessor address.

Example c) illustrate situation when the destination node is the neighbour of the transferring one then destination and transferring addresses are set to the same value by the transferring node. The probability that link between the destinator and the transferring node will be chosen is 1, probabilities of other links equal to 0.

Example d) is a situation when a transferring node is also a destination node, what means that all the elements of the *i*-row of the [*AMp*] matrix are set to zero.

Such an approach gives us four variants of the hot-potato protocol, namely:

1. simply hot-potato i.e. presence of the destinator or the predecessor is not considered during the transferring process,
2. with destinator consideration,
3. predecessor is known and is considered,
4. both predecessor and destinator are considered.

All these variants can be described by [*AMp*] matrix but only for 1st and 2nd variants [*AMp*]^{h} matrix determinates the probability of achieving a node with *h* hops [6]. To illustrate the presented considerations, an example of a simple network, which is shown in Figure 2, will be used.
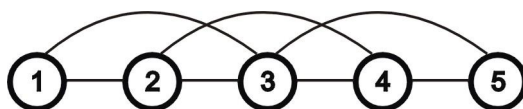

Fig. 2. Example of a simple network presented in graph form

The graph from Figure 2 is described by following matrix.

$$[AMp] = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{3} & 0 & \frac{1}{3} & \frac{1}{3} & 0 \\ \frac{1}{4} & \frac{1}{4} & 0 & \frac{1}{4} & \frac{1}{4} \\ 0 & \frac{1}{3} & \frac{1}{3} & 0 & \frac{1}{3} \\ 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 \end{bmatrix}$$

Assume that 5th node is the destination node the [*AMp*] matrix is assigned as [*AMp*]$_5$ and is shown below.

$$[AMp]_5 = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{3} & 0 & \frac{1}{3} & \frac{1}{3} & 0 \\ \frac{1}{4} & \frac{1}{4} & 0 & \frac{1}{4} & \frac{1}{4} \\ 0 & \frac{1}{3} & \frac{1}{3} & 0 & \frac{1}{3} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{1}$$

It should be noticed that if the destinator is the 5th node, the 5th row is zeroed and the graph from Figure 2 is modified follows: all links to 5th node are unidirectional. In this example, values in 5th column of $[AMp]_5$ matrix gives us information about the probability of getting to the 5th node with one hop; analyzing (1): it is impossible to achieve node 5, with one hop, from 1st and 2nd node whereas achieving from nodes 3rd and 4th is possible, with probabilities of 1/4 and 1/3 respectively.

Using the second variant of the hot-potato protocol, the network from Figure 2 must be modified by eliminating of some links or by changing them from bidirectional into unidirectional. Assume again, that 5th node is the destination node the example network for the second variant of hot-potato protocol can be described by the graph presented in Figure 3.
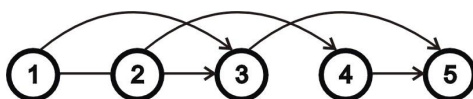

Fig. 3. Graph described the example network in which the second variant of the hot-potato protocol was implemented

For this case the $[AMp]_5$ matrix is presented below.

$$[AMp]_5 = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{3} & 0 & \frac{1}{3} & \frac{1}{3} & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (2)$$

Analyzing the values in 5th column, just like analyzing (1), there is possibility to achieve 5th node, with one hope, only from 3rd and 4th nodes, but now it is a certain event.

Presented network is an example which shows that second variant of the hot-potato protocol gives the same traffic results (in connection to 3rd and 4th node) as the optimal routing protocol i.e. based on the shortest-path metric [5]. Of course this is not typical situation, for describing the efficiency of the hot-potato protocol it is proposed a dedicated for a particular network method which is described in the next paragraph.

3. Assesment of the effectiveness of the hot-potato protocol variants

One of the critical parameter in WSN networks is so-called Expected Number of Transmissions (ETX) [7]. This parameter is determined experimentally and is used as a routing metric. The proposed method of analysis allows to determine $ETX_{i,j}$ between *i*-th and *j*-th nodes using the analytical method utilizing the following formula:

$$ETX_{i,j} = \sum_{h=1}^{m} h \cdot p_{i,j}(h) \tag{3}$$

where: m satisfies the following relationship $\bigwedge_{h>m} p_{i,j}(h) = 0$ and $p_{i,j}(h) = amp_{i,j}$, $amp_{i,j}$ is an element of the $[\boldsymbol{AMp}]_j^h$ matrix.

In most cases, m is infinite value the estimator of ETX has to be used. Estimator is assigned as $\hat{ETX}$ and depends on m value – the m is bigger the $\hat{ETX}$ is more accurate. Assessment of the effectiveness of the hot-potato protocol variants refers to a particular network. Taking in to account that "last-mile" smart lighting communications networks consist one access point and n nodes. The ETX for particular network is the arithmetic mean of all connections between the access point and nodes. For example, network described by (1) and assuming that node number 1 is an access point the $\hat{ETX}_{1,5}(m)$ values are presented in Figure 4, and the individual values of $p_{1,5}(h)$ in the Table 1.

Table 1. Probability of getting to the node 5 form the node 1with vs. number of hops

h	1	2	3	4	5	6	7	8	9	10
$p_{1,5}(h)$	0	0.125	0.139	0.1	0.097	0.076	0.069	0.057	0.05	0.042

The sum of probability values for ten consecutive hops is around 0.751 what means that $\hat{ETX}_{1,5}(10){=}3.8$ is still not accurate – the estimator is accurate when sum of probabilities is close to 1, thus sum of $p_{i,j}(h)$ can be a measure of estimator inaccuracy. To compare: the sum of probability values for twenty consecutive hops is around 0.948 and $\hat{ETX}_{1,5}(20){=}6.6$.
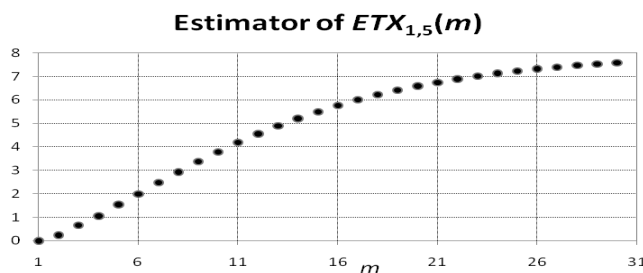

Estimator of $ETX_{1,5}(m)$

Fig. 4. Exemplary chart of estimator values vs. number of components calculated from (3)

Above example give us information that to communicate from node number 1 to node number 5 using the 1st variant of the hot-potato protocol eight hops are required, whilst using any of shortest-path (SP) depending routing protocol

only 2 hops are required, what means that in this case proposed solution is four times worse than using optimal protocol. What can be formally described as:

$$E_{i,j} = \frac{ETX_{i,j}}{SP_{i,j}}$$ (4)

where: $SP_{i,j}$ is the length of the shortest path between i and j nodes and $E_{i,j}$ is the effectiveness metrics. In this case $E_{1,5}(m = 30) \cong 3.78$. Further E_i denotes also the effectiveness of the protocol in the particular network in which i node is an access point.

The presented example was the worst case because path 1-5 was the longest in the network described by (1). For other paths of the same network, effectiveness of the 1st hot-potato protocol variant are as follow: $E_{1,2}(m = 30) \cong 3$; $E_{1,3}(m = 30) \cong 2.34$; $E_{1,4}(m = 30) \cong 2.5$. E_1 is calculated as fallow:

$$E_1(m = 30) = \frac{E_{1,2} + E_{1,3} + E_{1,4} + E_{1,5}}{4} \cong 2.9$$
.

E_1 informs us how many times the hops should be performed in the communication between the access point and the other nodes in compare to any of SP routing protocol. The communication between the access point and the other nodes using any variant of hot-potato protocol takes equal or less time than E_1 multiplied by information transmission time because one of the positive features of hot-potato is no delaying during the transfer process.

Using the 2nd variant of the hot-potato protocol $E_1(m = 30)$ parameter equals to 1.1. Such a positive outcome, as against to 1st variant, is due to one of two conditions making the 2nd variant efficient − it is efficient when network is small or degree of the access point is high. Here the first condition has been met.

In real "last-mile" communications systems dedicated to smart lighting any of above conditions is difficult to meet. Firstly because networks consists tens of nodes, secondly access points cannot cover many nodes by their range because they are located farther away from the lamps than distance between neighbouring ones. The situation is particularly critical when PLC is used as the medium, because in the case of WSN access points can be equipped with better (than normal nodes) antennas. The example of low efficiency can be only three times bigger network, actually being a link consisted of fifteen nodes. Using even the 2nd variant: $\hat{ETX}_{1,15}(100) = 36.7$ so $E_{1,15}(m = 100) \cong 5.24$ with the accuracy only on the level of 0.85.

This paragraph can be concluded that modification (2nd variant) of the original hot-potato protocol (1st variant) gives positive and measurable results but they are insufficient to provide fast and reliable communication, taking into account the size of the real "last-mile" communications network for road and street smart lighting control systems.

Using the same methods of the assessment, in the next paragraph the 3rd and the 4th variants of the hot-potato protocol will be analyzed.

4. Specific topology of last-mile smart metering network

As it was said before, the "last-mile" communications networks for road and street smart lighting control systems create a specific topology. A link topology causes the 3rd variant of the hot-potato protocol can be particularly efficient and moreover it can be analysed using the analytic method, which was already presented, but to achieve it one more system solution must be met − namely the list of neighbours in every node must be changed. The changes depend on dividing the list of the neighbours into two lists: the list of forwarding neighbours and the list of backwarding ones. The graph of the network, presented in Figure 2, modified by including only the list of forwarding neighbours in connectivity from node 1 to node 5 is presented in Figure 5.
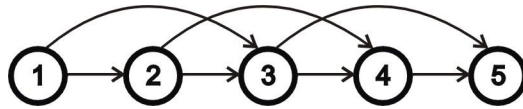

Fig. 5. Graph described connectivity between node 1 and 5 for the example network in which the third variant of the hot-potato protocol was implemented

For this case the $[\boldsymbol{AMp}]_5$ matrix is presented below.

$$[AMp]_5 = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

Comparing graphs presented on Figures 3 and 5, the differences are obvious but at first glance they seem to be small, what is the result of using only 5-nodes network as example. The effectiveness of the 3rd variant of the hot-potato protocol for the exemplary network in connection between nodes 1 and 5 is described by following parameters $ETX_{1,5} = 2.875$, $E_{1,5} = ETX_{1,5}/2 = 1.4375$. Obtained results the results require two comments: 1) no estimation is required because *m* has finite value equals to 4, 2) factor *E* equals to 1.4375 should be regarded as very good.

When further analysis of 3rd variant of the hot-potato protocol is being done a serious defect of the proposed method is easy to observe. This defect can be explained by the graph in Figure 6, connectivity from node 1 to 4.

Fig. 6. Defect of the 3rd variant of the hot potato protocol

In this example the defect occur, when information from node 1 to node 4 is transferred via node 5. The probability of such a situation is very high and equals to 0.375. Node 5 has no connection to node 4 so that information cannot be transferred. On the one hand this defect eliminate 3ʳᵈ variant from use but on the other hand the defect can be eliminated by using 4ᵗʰ variant of the hot potato protocol. Using 4ᵗʰ variant of the hot potato protocol the graph from Figure 6 is modified to the form presented in Figure 7.
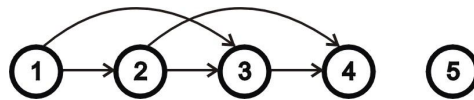

Fig. 7. Defect elimination – graph representation of the expletory network for 4ᵗʰ variant of the protocol, connectivity from node 1 to node 4

The effectiveness of the 4ᵗʰ variant of the hot-potato protocol for exemplary network is summarized in the Table 2 below.

Table 2. Parameters of the 4ᵗʰ variant of the hot potato protocol

to node	$ETX_{1, node}$	$E_{1, node}$	m
2	1	1	1
3	1.5	1.5	2
4	2.25	1.125	3
5	2.875	1.14375	4

If there is no need to estimate, m means the maximum number of hops. Data collected in above table allow to calculate E_1 parameter which is around 1.19.

Knowing the fact that the hot-potato protocol does not need any delay in transferring process obtained traffic parameters are comparable to those obtained using any of SP depending routing protocol.

Small, exemplary network was used for analysis and to explain its method. At the end of considerations, a real, very long (40-nodes) street light line will be analyzed. Results obtained for the worst case (communication from node 1 to 40) of 40-nodes network are presented. They are $m = 39$, $ETX_{1,40} = 26.22$, $E_{1,40} = 1.31$.

5. Conclusions

Road and street smart lighting systems can be controlled by communications networks which use the hot-potato protocol as the routing protocol. This is a new application area of this protocol. The proposed analysis method allows not only to determinate the effectiveness of proposed solutions but also allows to determinate many of traffic and protocol parameters such as maximum time of response or probability of the failure in a communication process. This computer method, based on the graph theory, can be applied also in access

points because their computational power allows both for a topology control as well as dynamically adjust of protocol parameters. This paper shows in details why only 4th variant of the hot-potato protocol may be used as a result of the specific topology created by road and street lighting systems.

Summarizing, 1st, "pure" version is inefficient; 2nd version would be efficient only for small networks and only if the communication range of access points was a large – none of these conditions can be met, either using wireless or PLC techniques; taking in to account the specific topology and the size of the road and street lighting networks the 3rd version should give the desire effect but just the specific topology caused the "blind curve problem", what disqualifies this variant for use in presented area; the disposal of the blind curve is directing to the destinator during the transfer process if the destinator is on the list of the neighbours of the transferring node. Thus, the efficient variant can only be the 4th one, being combination of 2nd and 3rd variants.

The hot-potato protocol applicability, regardless of its variant, provides all the advantages of using not memory greedy and heuristic routing protocols. Proposed system solutions are not without significance, taking into account the new regulation [8] for modern solution in road and street lighting.

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