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SPECIAL SECTION

Three methods of selecting a smart meter for data concentration in the automatic meter reading last mile network

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Abstract. This paper proposes three methods of the optimal smart meter selection for acting as a data concentrator in the automatic meter reading last mile network. The study explains the reasons why the selected smart meter should also act as a data concentrator, in addition to its basic role. To select the smart meter, either the reliability of communication or the speed of the automatic meter reading process was considered. Graph theory is employed to analyse the last mile network, described as sets of nodes and unreliable links. The frame error ratio was used to assess the unreliability whilst the number of hops was used to describe the speed of the reading process. The input data for the analysis are qualitative parameters determined based on observations in the real, operated last mile networks as well as their typical topological arrangements. The results of the research can be useful in the last mile network migration process, which uses concentrators to the networks without them, or during the process of newer last mile network implementation, where data concentrators are no longer applicable. The efficiency of the proposed methods is assessed measurably.

Keywords: smart meter; AMR; last mile network; network optimization; Industrial IoT.

1. INTRODUCTION

In automatic meter reading (AMR) systems, the last mile networks are connected to the IP (Internet Protocol) networks [1]. Similar to the concept of the Industrial Internet of Things (IIoT), various methods of accessing the IP network are used. In AMR most popular methods are Ethernet technology and data transmission over Global System for Mobile Communication (GSM). In smart metering (SM), which is one of the areas of AMR application for electricity consumption profiles reading, wireless local area network (WLAN) technology is not popular. The main difference between SM and IIoT is the method of terminal nodes connecting to the IP network. In IIoT, terminals are directly connected to the IP network or are connected via power line communication (PLC) links [2–4], whilst residential smart meters are connected to the IP network via a data concentrator. Smart meters equipped with GSM modems are rare. The data concentrator together with hundreds of smart meters form the last mile network. The communication technology in last mile networks is based on short-range devices such as PLC or ISM (industrial, scientific, and medical radio bands – also known as RF) [5]. In order to increase the range of the last mile network operation, a multi-hop technique is used, just like in wireless sensor networks (WSN) [6–8]. Thus, only a few smart meters are directly connected to the data concentrator.

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During the transmission process, the meters act mostly as intermediary nodes and sometimes as terminal ones. The data concentrator is usually installed next to an MV/LV transformer, hence its name: transformer station data concentrator (TSC) [9].

Modern smart meters are equipped with M-Bus [10, 11] and/or Modbus [12] interfaces. It facilitates the installation of a few communication modules in one meter [13], where each of the communication modules can use a different communication technology (which is also due to the progressing miniaturization of electronic components). Adopting such solutions makes it possible to realize and utilize last mile networks more flexibly while increasing their security, reliability, quality, and productivity, facilitating the migration process, e.g. from RF to PLC. Currently, two migration processes can be distinguished in the last million networks: migration from one technology to another [14] and structural migration.

Structural migration consists in eliminating the TSC and moving its functions to one of the smart meters, which may also act as local metering concentrator (LMC) [9]. Only LMC smart meter has to be equipped with two communication units, e.g., RF or PLC and GSM.

This work touches upon a novel approach in the last mile networks structural solutions, i.e., replacing TCS by a smart meter. The benefits of introducing this solution are:

- Lower last mile network creation and operation costs.
- Elimination of smart meters – TCS links, which are often unreliable due to the long distance between a transformer and an edge of a last-mile network.

- No need for the maintenance of TSCs involving complex procedures assuring the safety of the MV/LV transformer station.
- Increasing last mile network reliability, quality, and productivity (reading speed).

Replacing TSC with the smart meter, apart from the above-mentioned benefits, causes also a problem – a solution for which the author offers in this paper. The problem consists in choosing parameters of the optimal smart meter, which additionally is to work as LMC.

Reading speed is an important parameter in many aspects of smart metering system evaluation. Typically, the smart meter is queried every 15 minutes [15]. Although there are situations where a single smart meter is polled every 5 minutes [16] and even every minute [17]. Knowing the fact that there are several hundred smart meters in the network, not only the number of hops is critical, but also the reliability of the readings to minimize the number of time-consuming repetitions.

The proposed methods of finding the optimal smart meter are based on parts of the graph theory [18]. The three proposed methods are:

- The method of the smallest average minimum length path.
- The method based on path reliability.
- The method for routing protocols based on the multipath technique.

All proposed methods require the description of the last mile network in the form of a geometrical random graph.

2. METHODS OF SELECTING THE OPTIMAL SMART METER

2.1. Last mile network description

The description of the last mile network is necessary for further analysis. The topology of last mile networks may be described by geometrical random graphs [19]. The graph consists of a set of vertices, a set of edges, and a set of radii (which represents a range, or quality parameters as the author described it in [20]). Resource data for the last mile description are obtained in numerous ways, depending on the technology in which the last mile network was implemented. If the network is realized in RF technology, a set of neighbouring nodes is downloaded from every node, whilst in PLC technology, sets of terminal nodes are downloaded from the promoted switching nodes [21] only. Apart from the list of neighbouring nodes, two more types of parameters must be downloaded for the quality of links assessment:

- Counters of received error-free response frames.
- Counter of injected response frames.

The list of neighbouring nodes consists of their addresses. There is one counter of received error-free response frames for each neighbouring node. There is only one, global counter of injected response frames per smart meter. Injected frames are the frames transmitted by the node as a result of information generation in this node, not by relaying a frame that was injected into the network by another node.

The knowledge of the network topology and the quality of its links is used to determine the location of the smart meter, which is to act as a concentrator. Routing problems are not considered in this paper.

The use of graph theory (for the problems presented in this paper) is illustrated using the following, simple example. A last mile network of 10 nodes (smart meters) is given as it is shown in Fig. 1.

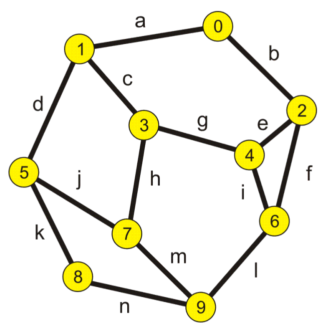

Fig. 1. An example of a last mile network

Using the procedure described in [20] the set of minimum-length paths, which are connecting nodes, are determined and

Table 1
The set of minimum-length paths

Node	0	1	2	3	4	5	6	7	8	9
0		a	b	ac	be	ad	bf	ach, adj	Adk	Bfl
1	A		ab	c	cg	d	abf, cgi	ch, dj	Dk	chm, djm, dkn
2	B	ab		eg	e	bad	f	lgh, egh	fln	fl
3	Ac	C	eg		g	cd, hj	gi	h	hmn, cdk, cjk	hm
4	Be	Cg	e	g		gcd, ghj	i	gh	iln	Il
5	Ad	d	bad	cd, hj	gcd, ghj		jml, knl	j	k	jm, kn
6	Bf	abf, cgi	f	gi	i	jml, knl		lm	ln	L
7	ach, adj	ch, dj	lgh, egh	h	gh	j	lm		jk, mn	M
8	Adk	dk	fln	hmn, cdk, cjk	iln	k	ln	jk, mn		N
9	Bfl	chm, djm, dkn	fl	hm	il	jm, kn	l	m	n	

presented in Table 1. It is possible to determine them, without any procedure but it is time-consuming even on a 10-node last mile network. In practice, last mile networks contain hundreds of smart meters so "manual" analysis is impossible.

When creating Table 1, it was assumed that all links presented in Fig. 1 are bidirectional.

2.2. Method of the smallest average minimum length path

The proposed method of the smart meter designation for acting as a data concentrator consists of three steps:

1) From the set of minimum lengths paths specify the length of minimum paths between each node.

2) For every node, calculate the average value of minimum length paths, using the following formula:

$$d_{\text{avr}}(i) = \frac{1}{N-1}\sum_{j=0}^{N-1} d(i,j), \tag{1}$$

where N is the number of smart meters in the last mile network and d is the length of the minimum path (or paths) between two nodes.

3) Choose the node with the smallest value of d_{avr}, this smart meter should act as a data concentrator.

Using the set of minimum length paths presented in Table 1, the minimum path length values for every pair of nodes are included in Table 2.

Table 2
Minimum path length values (the number of edges)

Node	0	1	2	3	4	5	6	7	8	9
0		1	1	2	2	2	2	3	3	3
1	1		2	1	2	1	3	2	2	3
2	1	2		2	1	3	1	3	3	2
3	2	1	2		1	2	2	1	3	2
4	2	2	1	1		3	1	2	3	2
5	2	1	3	2	3		3	1	1	2
6	2	3	1	2	1	3		2	2	1
7	3	2	3	1	2	1	2		2	1
8	3	2	3	3	3	1	2	2		1
9	3	3	2	2	2	2	1	1	1	

The values of d_{avr} were calculated by substituting data from Table 2 into formula (1), and they are presented in Table 3.

Table 3
Values of d_{avr} for the last mile network presented in Fig. 1

Node	0	1	2	**3**	4	5	6	7	8	9
d_{avr}	2.11	1.89	2	**1.78**	1.89	2	1.89	1.89	2.22	1.89

From the data in Table 3, it follows that smart meter number 3 should function as a data concentrator.

Using the fact that the information exchange is between the data concentrator and a smart meter, and not between smart meters, the last mile network topology will look as it is shown in Fig. 2.

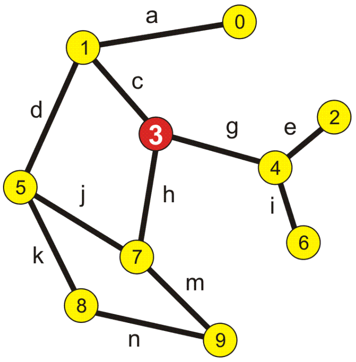

Fig. 2. Optimal last mile network topology with the data concentrator in the smart meter number 3

The above structure can also be presented as the set of the minimum length paths from/to node 3 as it is included in Table 4.

Table 4
The set of minimum-length paths from/to node 3

Node	0	1	2	4	5	6	7	8	9
3	ac	c	eg	g	cd, hj	gi	h	hmn, cdk, hjk	hm

The method presented in this paragraph allows us to choose an optimal node to function as the data concentrator. The optimization criterion is the number of hops – the smaller the number, the shorter the communication time.

2.3. A method based on path reliability

The frame error ratio (FER) may be used to describe the reliability of the links. The FER value should be calculated for the frames, which have the same length [22], using the right side of the following formula:

$$FER = \frac{R_e + M}{R_e + R_{ef} + M} = \frac{R_e + M}{T} = \frac{T - R_{ef}}{T}, \tag{2}$$

where R_e is the number of erroneous frames received from a specific node and R_{ef} is the number of error-free frames from the same, specific node, M is the number of missed frames and T is the total number of transmitted frames by a specific node.

The value of T is the sum of R_e, R_{ef}, and M. To assess the FER of the link (in one direction) the value of R_{ef} is downloaded from one node and the value of T is downloaded from the node at the other end of the link. Nodes do not have any R_e and M counters because they cannot notice if frames are missed, and they cannot analyse erroneous frames (e.g., a source address).

The smaller the value of FER, the better the reliability of the link. FER takes values between 0 and 1 and can be regarded as the probability (determined from the sample) of receiving an erroneous frame or not receiving it at all (the frame is missing). In this work, *FER* was always calculated for the longest possible frames which the smart meter can transmit, i.e., response frames those transfer the energy consumption profile. Every node has counters injected into the network: commands, response and acknowledge frames.

Knowing the fact that *FER* values usually differ in each transmission direction (links do not have symmetrical quality) [22], it is necessary to make a *FER* assessment in both directions and determine the resultant value of *FER*. It is proposed to use formula (3) for the resultant *FER*:

$$FER_x = 1 - \left(1 - FER_{i\_j}\right)\left(1 - FER_{j\_i}\right). \tag{3}$$

Note, that x indicates the link, and i and j indicate the number of the node. For example, node 1 received from node 5 ten thousand frames, 889 of which were erroneous, and node 5 received from node 1 twenty thousand frames, 1846 of which were erroneous, using (2) FER_{1_5} is 0.0889 and FER_{5_1} is 0.0923. The resultant *FER* of the bidirectional link d, which connects nodes 1 and 5 is 0.173, which was calculated using (3).

Examples of the values of the resultant *FER* for the last mile network shown in Fig. 1 are presented in Table 5.

Table 5
Examples of the values of the resultant *FER*

FER_a	FER_b	FER_c	FER_d	FER_e	FER_f	FER_g
0.173	0.149	0.088	0.173	0.086	0.087	0.065
FER_h	FER_i	FER_j	FER_k	FER_l	FER_m	FER_n
0.091	0.07	0.141	0.085	0.122	0.089	0.241

The resultant values of *FER* for all links in the last mile network may be used to calculate the *FER* of the path with the use of the following formula:

$$FER_{x\cdots z} = 1 - \left[(1 - FER_x)\cdot \;\cdots\; \cdot (1 - FER_z)\right], \tag{4}$$

where $x \cdots z$ indicates the set of links that create a path.

Using the formula (4) and data from Tables 1 and 5, the *FER* values for all possible minimum length paths were calculated and are included in Table 6.

The next step in this method is selecting the best (with the smallest value of *FER*) minimum length paths for every possible connection between two nodes. The data from Table 6, after eliminating redundant worse paths, are presented in Table 7.

The last step in this method is the node selection. The node which has the smallest average *FER* in connection to other nodes should be selected, and this smart meter should act as a data concentrator. Table 8 contains average *FER* values calculated from the *FER*s between a particular node and the other nodes.

The data contained in Table 8 show that the smart meter number 3 should act as the data concentrator.

Table 6
FER values of all minimum length paths

1	0.17								
2	0.15	0.3							
3	0.25	0.09	0.15						
4	0.22	0.15	0.09	0.07					
5	0.32	0.17	0.42	0.25 0.22	0.29 0.27				
6	0.22	0.36 0.21	0.09	0.13	0.07	0.31 0.39			
7	0.31 0.41	0.17 0.29	0.25 0.22	0.09	0.15	0.14	0.2		
8	0.37	0.3	0.39	0.37 0.3 0.28	0.38	0.09	0.33	0.21 0.31	
9	0.32	0.17 0.35 0.43	0.2	0.17	0.18	0.22 0.3	0.12	0.09	0.24
Node	0	1	2	3	4	5	6	7	8

Table 7
FER of best minimum length paths

1	0.17								
2	0.15	0.3							
3	0.25	0.09	0.15						
4	0.22	0.15	0.09	0.07					
5	0.32	0.17	0.42	0.22	0.27				
6	0.22	0.21	0.09	0.13	0.07	0.31			
7	0.31	0.17	0.22	0.09	0.15	0.14	0.2		
8	0.37	0.3	0.39	0.28	0.38	0.09	0.33	0.21	
9	0.32	0.17	0.2	0.17	0.18	0.22	0.12	0.09	0.24
Node	0	1	2	3	4	5	6	7	8

Table 8
Average *FER* values

Node	0	1	2	**3**	4	5	6	7	8	9
FER_{avr}	0.26	0.19	0.22	**0.16**	0.18	0.24	0.19	0.18	0.29	0.18

2.4. Method for multipath protocols

In SM last mile networks, especially based on RF technology, flooding-type protocols are very often used as routing protocols [23, 24]. In this case, a multipath technique is applied, independently from the multi-hop technique. The multipath technique is used to increase the reliability of communication by sending the same information via different routes. The *FER* of a multipath connection can be calculated using the following formula:

$$FER_{\mathrm{MP}}(i,j)=\prod_{k=1}^{n} FER_k\,, \tag{5}$$

where $FER_{\mathrm{MP}}(i,j)$ is the FER between i-th and j-th node connected with the use of the multipath technique, whilst FER_k is the FER of the k-th path, which is a part of the multipath. Using formula (5) for the FER of the individual paths presented in Table 6 values of FER_{MP} were calculated and are presented in Table 9.

Table 9
$\mathrm{FER}_{\mathrm{MF}}$ values for all possible connections

1	0.17								
2	0.15	0.3							
3	0.25	0.09	0.15						
4	0.22	0.15	0.09	0.07					
5	0.32	0.17	0.42	0.055	0.078				
6	0.22	0.076	0.09	0.13	0.07	0.121			
7	0.127	0.049	0.055	0.09	0.15	0.14	0.2		
8	0.37	0.3	0.39	0.032	0.38	0.09	0.33	0.065	
9	0.32	0.026	0.2	0.17	0.18	0.066	0.12	0.09	0.24
Node	0	1	2	3	4	5	6	7	8

To select the optimal smart meter, average values of FER_{MF} must be calculated for every node. Using the data from Table 9 average values of FER_{MF} were calculated and are presented in Table 10.

Table 10
Average FER_{MF} values

Node	0	1	2	3	4	5	6	**7**	8	9
FER_{MFavr}	0.24	0.14	0.21	0.12	0.15	0.16	0.15	**0.11**	0.24	0.16

The data contained in Table 10 show that the smart meter number 7 should function as the data concentrator.

3. ANALYSIS OF THEORETICAL RESULTS

The expected result of the analysis is the node number, which identifies the optimal smart meter to be utilized as the data concentrator. Three methods were proposed and used in the analysis of the 10-node example network, presented in Fig. 1.

Node 3 would be the optimal node using the first and second methods, whilst node 7 would be the optimal node using the third method. In practice methods first and second very often produce the same results, but not always, e.g., node 4 would be the optimal node if the FER of the c-link were bigger. Producing the same results by using method 1 and method 2 is easy two explain: method 1 prefers short paths (small number of hops), and method 2 prefers low paths with FER. The conditions that ensure a low FER of the path are a small number of hops and/or a low FER of the links. Thus, the number of hops is a common factor for both methods. Method 3 produced a different result but having analysed the data presented in Table 10, it may be concluded that node 3 is "second in queue" to be the optimal node. Method 3 prefers connections based on multipaths. It is because the multipath technique has a strong impact on FER decreasing, which is easy to observe by comparing the results included in Tables 8 and 10.

To compare results obtained by using method 1 with results obtained by method 2 or 3, data included in Tables 3, 8, and 10 should be normalized and presented, e.g., in the form of charts, like those shown in Fig. 3. They should be normalized because they are not the same quantities.

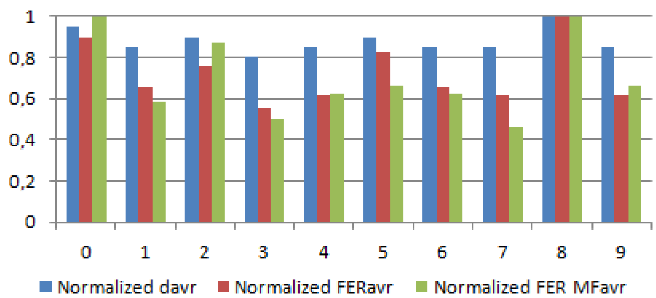

Fig. 3. Normalized values of d_{avr}, FER_{avr}, and FER_{MFavr} calculated for smart meters numbered from 0 to 9

It is easy to notice from Fig. 3 that node 8 is the worse to function as the data concentrator.

If the application of a particular method is not imposed, the use of the following formula is proposed to aggregate and unify parameters obtained by different methods:

$$u_{\mathrm{avr}}=a_1\hat{d}_{\mathrm{avr}}+a_2\widehat{FER}_{\mathrm{avr}}+a_3\widehat{FER}_{\mathrm{MFavr}}\,, \tag{6}$$

where a_1, a_2 and a_3 are the applied method metrics.

Metrics may have values between 0 and 1, and the sum of them must be 1.

Unified parameters included in Table 11 were calculated for the last mile network presented in Fig. 1, assuming that $a1=a_2=a_3=1/3$.

Table 11
Parameters calculated using (6) and data from Tables 3, 8 and 10

Node	0	1	2	**3**	4	5	6	7	8	9
u_{avr}	0.95	0.7	0.85	**0.62**	0.7	0.8	0.71	0.64	1	0.71

A node that has the smallest parameter u_{avr} may be selected – this smart meter could function as a data concentrator.

The aggregation of the data obtained by different methods can help DSOs (distribution system operators) when they cannot decide which method is better for a particular network. In general, averaging with metrics facilitates a compromise.

4. PRACTICAL RESULTS AND PROPOSED METHODS VERIFICATION

Results were verified in the real conditions with the use of 70 smart meters. Smart meters were installed in the lab. Smart meters communicate using RF technology in 868 MHz ISM band [25]. A fragment of the testbed installation is presented in Fig. 4.

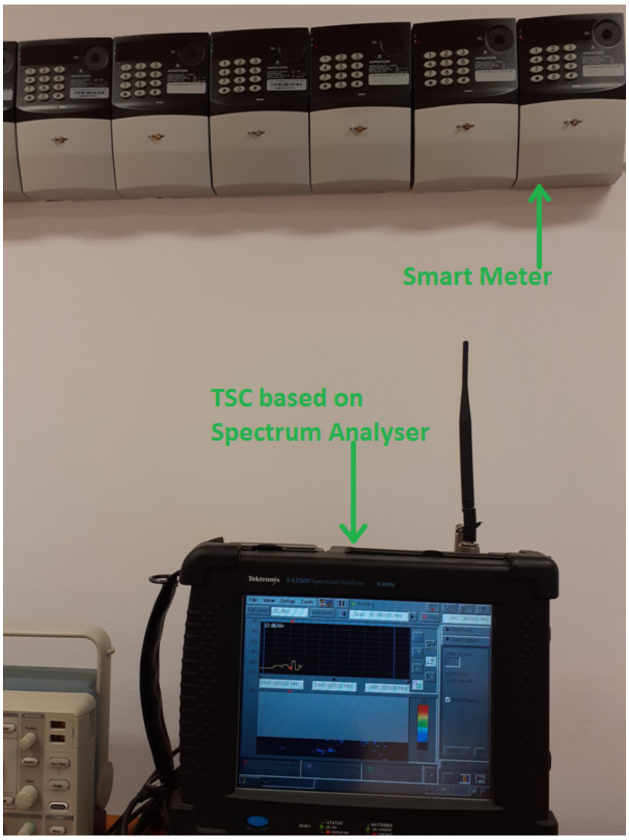

Fig. 4. Fragment of the testbed installation

Various topological forms were created during tests. The transmission power was regulated (set) to gain desired *FER* values (this is why TSC presented in Fig. 4 was used). Verification depended on comparing one, important traffic parameter, i.e., the speed of data reading. Parameters were obtained when the data concentrator was located in optimal place and random place. Optimal places were assessed using the method proposed in this paper. In more than 90% of cases, the results of conducted experiments met the expectations (results predicted theoretically with the use of the proposed methods). 99 experiments were conducted – 33 per method.

Using the first method, 29 results met expectations, and 4 results did not meet. Better traffic parameters were obtained for random localizations (not optimal), which actually were smart meters, which had an average minimum length path – d_{avr} values not much greater than the smallest one.

Using the second method, 28 results met expectations, and 5 results did not. In 5 cases, better traffic parameters were obtained when data concentrators were located in suboptimal localization probably because in this part of the experiments smart meters worked with ultra-low transmission power to provide high *FER* conditions.

Using the third method, the results of all experiments met expectations.

5. CONCLUSIONS

Out of the three proposed methods, the method of the smallest average minimum length path is most generally applicable. This is because, regardless of applied technologies or standards, nodes always have a list of neighbouring nodes. Downloaded lists from all last mile network nodes allow us to create the geometrical random graph. These data are sufficient to use the method of the smallest average minimum length path.

The geometrical random graph is also necessary when a method based on path reliability is used to find the optimal smart meter. Using this method, in addition to the list of neighbouring nodes, the quality parameters of the links to them are required. In this paper, FER was used, but in practice, the same results give the analysis of packet error ratio (PER). Relations between the FER (or PER) and signal-to-noise ratio (SNR) values can also be used to describe a link quality – there is a direct, though not linear, relation between them. Using SNR as the link quality parameter, similar to FER or PER, the length of the information unit should be considered. Additionally, when SNR is used, we also need to know the kind of applied modulation [26], because the *FER*(*SNR*) and *PER*(*SNR*) curves depend on the modulation type. Apart from FER, PER, or SNR, other quality parameters can be used in the analysis, e.g., link quality indicator (LQI) [25]. Using LQI, we have the data of the bigger resolution, because LQI is calculated independently from the length of frame. The method based on link quality cannot be applied if all links in the last mile network are faultless, i.e., $FER = 0$ or $PER = 0$ or *SNR*s of received signals have the highest possible values. This situation is only possible in theory.

The method for multipath protocols needs information about link quality, too. This method also uses the geometrical random graph. As with the first and second methods, the third method requires the graph to determine the lengths of the minimum paths, but additionally to determine the number of minimum length paths and the sets of links that create particular paths. This method is not applicable when the last mile network is based on the PRIME or G3-PLC interfaces [27, 28] because these interfaces do not support the multipath technique.

The use of the first method allows us to optimize the last mile network for the speed of data readings. The second method is used to optimize the reliability of the data reading process and to minimize the number of repetitions. The use of the third method facilitates both increasing the speed of data acquisition and ensuring high reliability of communication; however, this method has the disadvantage of being limited in use.

The efficiency of the proposed methods can be determined as the ratio of the median value from Tables 3, 8, or 10 (depending on the method) to the minimum value from the same table. The greater the ratio, the better the efficiency. For the network presented in Fig.1, the efficiency of using the first method is 1.06, the second method is 1.16, and the third method is 1.29.

In real SM last mile networks these ratios are bigger due to the greater number of smart meters in the network.

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