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Power Line Carrier Equipment Supporting IP Traffic Transmission in the Enterprise Networks of Energy Companies

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***Abstract*—**This article discusses the questions concerning of creating small packet networks for energy companies with application of high voltage power line carrier equipment (PLC) with functionality of IP traffic transmission. The main idea is to create converged PLC links between substations and dispatching centers where packet data and voice are transmitted in one data flow. The article contents description of basic conception of the network, evaluation of voice traffic transmission parameters, and discussion of header compression techniques in relation to PLC links. The results of exploration show us, that convergent packet PLC links can be very useful in the construction of small packet networks between substations in remote locations, such as deposits or low populated areas.

***Keywords*—**packet PLC; VoIP; time delay; packet traffic; overhead compression

I. Introduction

HIGH voltage (HV) power line carrier systems represent class of equipment, which is used in departmental networks of energy companies for data and voice transmission between high voltage substations (SS) and dispatching centers. For information transmission phase conductors or ground wires of high voltage lines are used. Typical voltage classes of the lines are from 35 to 1150 kV. PLC communication uses spectrum from 24 to 1000 kHz with channels multiple of 4 kHz grid. The typical bandwidths of PLC links are 4, 8, 12, 16, 24, 32 kHz.

In most cases high voltage line is the shortest path between substations. Some times for energy company application of power line carrier equipment for data and voice transmission is the most useful. On the one part there are no charges for construction of optical ground wire (OPGW) or microwave links, on other part amount of information need to be transmitted from the substation to control centre is very small. Usually payload of PLC link contents one or two voice channels and some data from substation monitoring systems (SCADA).

The newest types of PLC equipment support IP traffic transmission [1], [2]. Such class of PLC equipment could be named as **Packet PLC**. It allows creating convergent links, where packet voice and data are transmitted in one data flow.

The main purposes of the exploration are

- to define the area of pPLC links application in the enterprise network of energy companies.
- to create the basic model of network with pPLC application.
- to define types of transmitted information between nodes and their priority in overall traffic.
- to define characteristics of traffic transmission over pPLC links, optimal scheme of packet header compression, required bit rate for multi-segment pPLC link, time delay.

II. Place of Packet PLC Links in the Enterprise Network of Energy Company

Today, in telecommunication networks of energy companies we can notice the tendency to converged packet networks migration and phasing out equipment with frequency or time division of subscribers.

Customer solutions under the use of packet traffic, for example IP telephony provides a large number of services that are using regular phones will be either impossible or their cost will be several times higher.

Enterprise network of Energy Company contents of high bit rate backbone links with capacity STM-1 and more, depends on specified requirements of technological processes. Usually for such application OPGW and Microwave are used. OPGW for backbone links is installed on HV lines 220 and 500 kV. Length of OPGW links could reach hundreds kilometers with length of regenerator section more than 250 km.

But power grids have places where OPGW or other technology is not applicable. Typically it is 110 or 220 kV substations in distant areas such as deposits or mountainous terrain. In this case PLC often could be one useful technology.

Generally we could define two concepts of Packet PLC application in Power Companies Enterprise Network:

- Creating of bridge connection between areas of enterprise network. In this case pPLC could be either back-up channel for OPGW or Microwave, or separate solution.
- Creating of small networks with application of convergent pPLC links and integration to enterprise network.

In both cases application of pPLC provides the benefits related to packet networks interworking:

- Unified management of network nodes.
- The possibility of joining network nodes from different vendors using standardized protocols.
- Scalability of the network.
- Common principles of routing and traffic management.
- Flexible backup algorithms.

Schemes of both concepts representation are shown in Fig. 1 and 2

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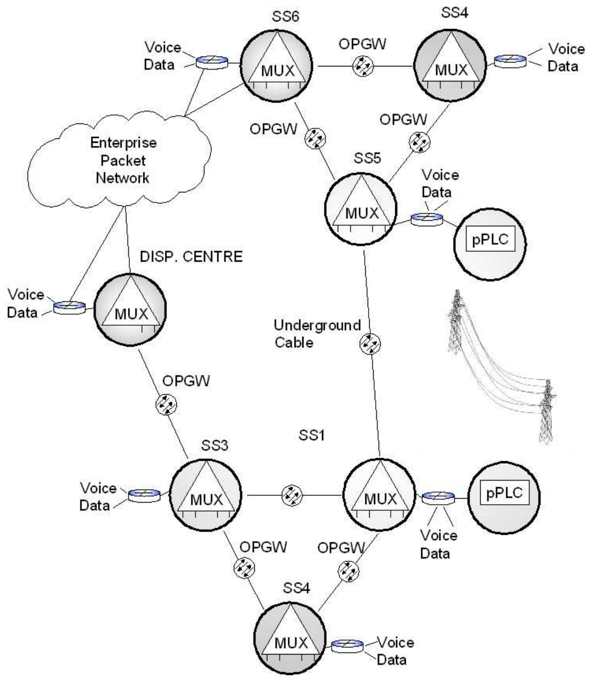

Fig. 1 Application of pPLC as back-up channel or interconnection of two segments of network

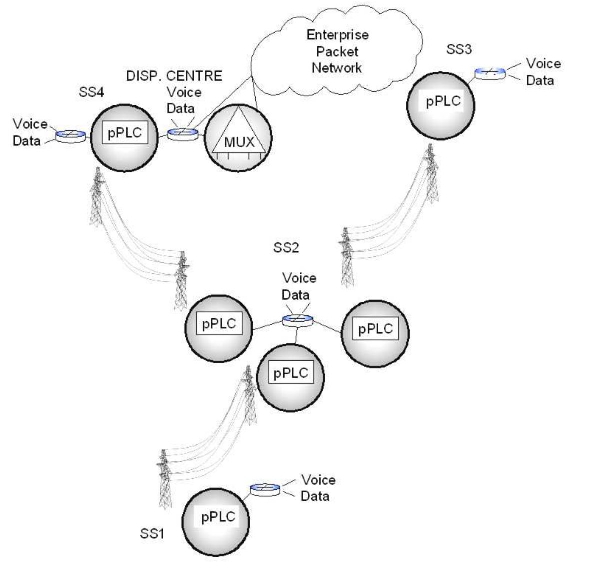

Fig. 2 Application of pPLC for creating of small networks between substations

Before we decide to use pPLC link for traffic transmission we need evaluate is this solution suitable for our purposes. We need to define, are the actual parameters of pPLC link allow reaching required parameters of traffic transmission: bit rate, time delay, packet loses.

Typical scheme of PLC link is shown in Fig. 3.

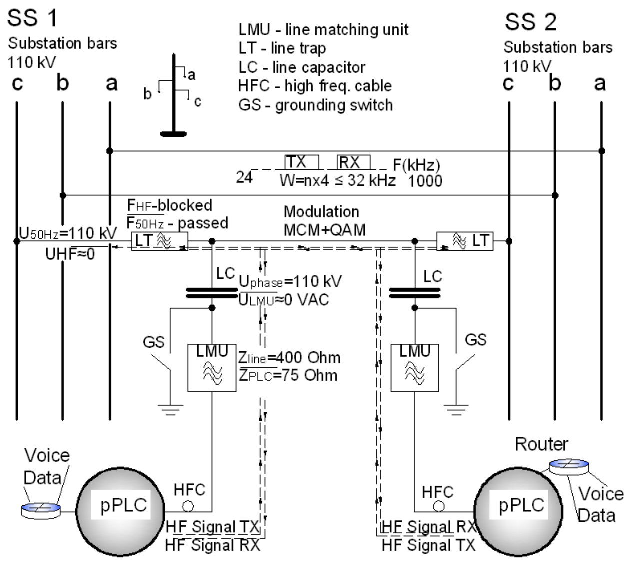

Fig. 3 Scheme of High Voltage Power Line Carrier Link

We have to notice that application of pPLC links has some limits which should be observed in project design. First of all, in most cases creating of carrier grade pPLC link depends on proper calculation of link attenuation and signal to noise ratio on input of the receiver. Parameters of signal transmission could be sufficiently different depend on type of high voltage line, voltage class has especially high impact.

Line attenuation and level of noise depend on a lot of factors, such as:

- Voltage class of the HV line.
- Length of HV the line.
- Coupling phase and method of coupling.
- Frequencies of link.
- Existing of taping lines.
- Weather conditions.

All of these factors have impact to the link behavior. Methodic of PLC link calculation are shown in [3]-[6].

For pPLC equipment the most important significance has SNR parameter, because maximal bit rate B of the link depends on SNR.

$$B = f(SNR) \quad (1)$$

$$SNR = P_{TX} - (A + K) - P_{NOISE} \quad (2)$$

Where:

P_{TX} – nominal output level of modulated signal;

A – sum of link components attenuation– phase conductor, line traps, line matching units, voltage transformers;

K – coefficient considering weather factor impact (signal transmission parameters degradation because of moisture, glazed frost at alias). For pPLC links could be accepted as 9 dBm.

Average level of noise in HV line depends on voltage class. In theTable 1 levels of noise corresponding to 100 kHz for HV lines with different class of voltage are shown [3]. Bandwidth of channel is 1 kHz:

Actual level of noise for defined bandwidth and frequency could be derived with application of equations (3) and (4) [3]:

$$P_{NOISE\ (f)} = P_{NOISE\ (100)} + 5 \cdot \lg(f/100) \qquad (3)$$

TABLE I
NOISE LEVEL FOR 1 KHZ BANDWIDTH

U, kV	Level of noise, dBm
6-35	-50
110	-40
220	-30
330	-30
500	-25
750	-20
1150	-20

$$P_{NOISE\ (\Delta f)} = P_{NOISE\ (f)} + 10 \cdot \lg(\Delta f) \qquad (4)$$

Approximate line attenuation of phase conductor and coupling devices could be derived as:

$$A = 0{,}00868 \cdot k \cdot \sqrt{f} \cdot l + 5 \qquad (5)$$

Where:
k– coefficient depending on HV line class, k=1,4 for 35 kV line, k=1 for 110 kV line, k=0,83 for 220 kV line;
f – maximal frequency of using band, kHz;
l – length of the HV line, km;
5 dBm – normalized value of attenuation inserted by coupling devices for both sides of HV line [6].

According to equations (2)-(5), SNR could be derived as:

$$SNR = P_{TX} - (0{,}008 \cdot k \cdot \sqrt{f} \cdot l + 5 + K) - P_{NOISE\ (\Delta f)} \qquad (6)$$

For our purposes practice interest is definition of maximal accepted length of the HV line depends on frequency with fixed values of SNR and output power. Maximal accepted length of the HV line allows us to define area of packet link application.

Dependence between SNR and maximal bit rate depends on PLC equipment performance and characteristics – type of coder and error correction mechanisms. Output power usually is fixed and depends on peak envelope power of transmitter and type of using modulation.

The maximal length of the HV line from equation (6) could be derived as:

$$l = \frac{P_{TX} - SNR - P_{NOISE\ (\Delta f)} - K - 5}{0{,}00868 \cdot k \cdot \sqrt{f}} \qquad (7)$$

Nominal output power of modulated signal depends on hardware realization of transmitter and used method of modulation. The most popular scheme of modulation using in pPLC equipment is MCM+QAM. Multi carrier modulation especially for channel bands more than 12 kHz provides flexible distribution of data to carriers subject to amplitude-frequency characteristic of the link.

For example characteristics of PLC equipment PowerLink 50 were observed. Output power of modulated signal with amplifier peak envelope power of 50 Watt will be 36 dBm [1]. Equipment provides the maximal bit rate with SNR equal 45 dBm. Values of bit rate for SNR=45 dBm are shown in the Table II.

Diagrams in Fig. 4, 5 show results of deriving l(*f*) for SNR=45 for different classes of the HV lines. Calculation shows that for SNR=45 dBm in our example 220 kV lines could not be used for pPLC links at all. But if we accept some step-down of required SNR up to 30 dBm we get longer distances and possibility to use PLC on 220 kV lines. Values of bit rate for SNR=30 dBm are shown in Table III. Results of deriving are shown in Fig. 6-8.

TABLE II
VALUES OF BIT RATE DEPENDS ON CHANNEL BANDWIDTH FOR SNR=45 DBM

W, kHz	B, kbps
4	32
8	64
12	114
16	156
24	244
32	320

TABLE III
VALUES OF BIT RATE DEPENDS ON CHANNEL BANDWIDTH FOR SNR=30 DBM

W, kHz	B, kbps
4	24
8	40
12	72
16	96
24	144
32	192

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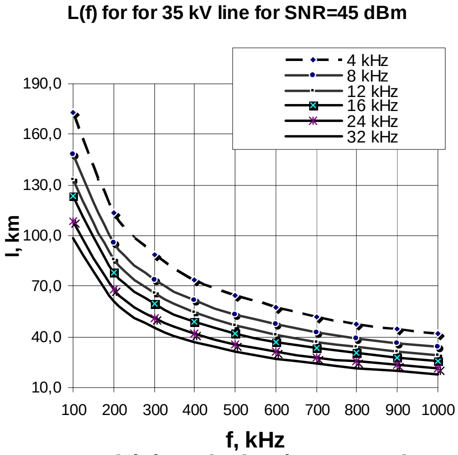

Fig. 4 l(f) for 35 kV line for SNR=45 dBm

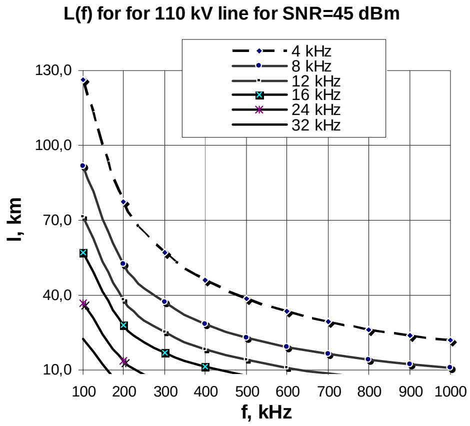

Fig. 5 l(f) for 110 kV line for SNR=45 dBm

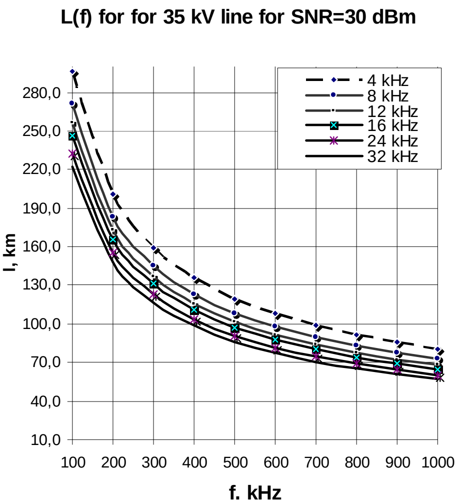

Fig. 6 l(f) for 35 kV line for SNR=30 dBm

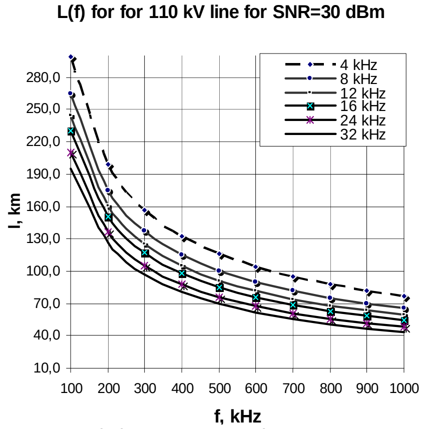

Fig. 7 l(f) for 110 kV line for SNR=30 dBm

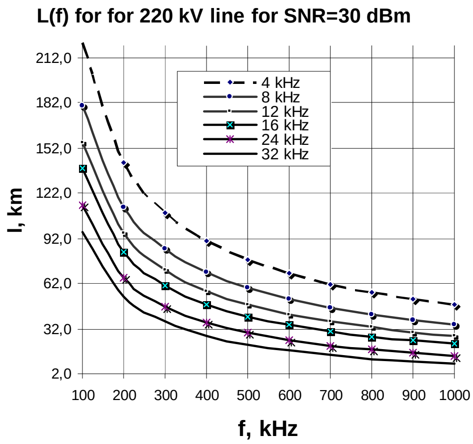

Fig. 8 l(f) for 220 kV line for SNR=30 dBm

Diagrams show that acceptable length of HV line decrease with increasing of frequencies. Fig. 9 shows relational benefit in distance and loss in bit rate for SNR=45 dBm and 30 dBm.

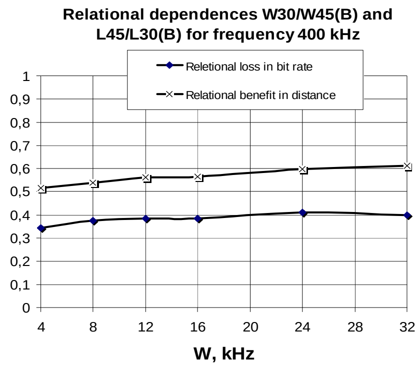

Fig. 9 Relational change of W and L for SNR 45 and 30 dBm

We do not consider 330 kV lines and higher for pPLC link creating because these lines are backbone of power grid and usually there OPGW is used.

Also from practical experience the performance of digital modulation on lines higher than 220 kV is poor because of high level of noise.

Implemented analysis shows that area of pPLC application is wide, but depends on required performance of link. On the one part we need safe the spectrum, on the other part wider bandwidth provides same bit rate with lower required SNR. For our specified example in case when we reduce requirements to bit rate on 30 % we could increase transmission range at more than 50 %.

Practical experience shows the most suitable area for pPLC equipment application are 35 and 110 kV lines with length less than 150 km. These lines typically are represented between substation on the deposits, low populated distant areas and small cities.

III. Basic Model of Network with pPLC Application

For definition of parameters of traffic transmission over convergent pPLC links we need create simple model of the network. Topology of the network corresponds to tree-type topology of HV lines in Power Grid. Main feature of considered network – presence of multi – segment links (MSC). Fig. 10 shows the simplest model of the network.

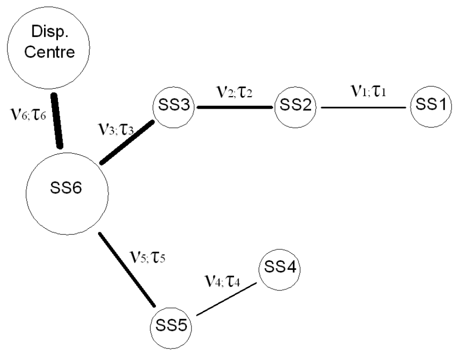

Fig. 10 Model of the network with pPLC links

In the observed model $\boldsymbol{\nu}$ – is payload from i substation, $\boldsymbol{\tau}$ – time delay of packets transmission for j link.

Model could be described by combined inequalities:

$$\begin{cases} \sum_{i=1}^{N} \nu_i \le B_{i(\max)} - K_i, \\ \sum_{j=1}^{N-1} \tau_j \le T_{\max}, \\ \prod_{j=1}^{N-1} P_j > 0{,}95 \\ \text{given } N \to \max \end{cases} \tag{8}$$

Where:

N – number of nodes (substations);

$B_{i(max)}$ – maximal achievable bit rate for link with maximal payload for multi – segment link;

T_{max} - maximal acceptable delay of transmission for multi segment link;

K_i - coefficient corresponding to decreasing of bit rate because low SNR during periods of bad weather;

P_i – availability of the link. For PLC links this parameter should be not less than 0,95;

Suggested model in general consider only two parameters – required bit rate and time of traffic transmission delay, but these two parameters mostly will define limitation in value of intermediate nodes. In most cases for multi – segment links nearest to the dispatching centre link must have the biggest bandwidth and bit rate to transmit information from other nodes to the centre. Therefore if bit rate of “last link” is not enough for data flow transmission it will be the first limitation for number of intermediate nodes. Notice, that we do not consider cases when information will be divided to two separate parallel links for one HV line. Further we will show that second factor - T_{max} is more important for multi – segment convergent pPLC links.

In the convergent channels we have types of traffic critical to time of transmission delay – such as voice. Segment j of multi – segment link increase overall time of transmission to τ_j. When time of transmission delay increases T_{max} it defines second limitation in number of intermediate links.

IV. Types of Information Transmitted Between Nodes and Their Priority in Overall Traffic

In the departmental network of Energy Companies a lot of types of information are transmitted. They could be divided in two groups:

- Mandatory for transmission.
- Miscellaneous.

Data in Table IV show the distribution of traffic to the groups.

During normal process of power grid operation traffic flow has relatively smooth character:

- SCADA system sends information only during startup and renews data with sporadic messages or by polling from server system.
- SFPA remote terminal unit sends messages to the server either over defined time period or by polling from server.
- Rate of dispatching voice channels using is nearly the same for each hour, with active decay during night time.
- Control of telecommunication equipment including power supply system, GPS routers implemented by

TABLE IV
Types of Information Transmitted between Substations and Dispatching Centre

Mandatory	Miscellaneous
Voice – dispatching voice channels/ Priority 1. Max. acceptable time delay T_d < 450 ms	Voice – other channels / Priority 4
Data from Supervisory for Control And Data Acquision (SCADA) system of substation/ Priority 2. Max. acceptable time delay T_d < 3000 ms.	E-mail service, Internet/ Priority 4
Monitoring of nodes with SNMP protocol Priority 2.	
Data from System of Power Flow Accounting (SPFA) of substation/ Priority 3 Periods of polling 15 or 30 minutes	

application of SNMP protocol. Data about condition of terminals is renewing only with messages indicated alarms.

- Voice channels for technical purposes are used by service stuff of substation for conversation during substation equipment maintenance.
- E-mail and Internet traffic are transmitted when bandwidth resources are available.

In case of faults or some operations on the switchyard traffic flow shortly could have peaks and some congestions could take place. Especially it is actually for traffic from SCADA system.

To avoid loses of priority traffic we need to apply suitable scheme of queue processing. Earlier was suggested the most sufficient method of traffic prioritization for pPLC links [7]. Method of Priority Queuing (PQ) supports four classes of services: highest, high, normal and low. Quality of service is regulated with buffer length. Such method provides guaranteed QoS of highest priority traffic even with in overloaded channel.

V. Characteristics of Traffic Transmission, Optimal Scheme of Overhead compression

To provide the performance of multi – segment link we need ensure that each hop in multi – segment pPLC link has sufficient bit rate for own and transit traffic transmission. In the serial link each further segment is bearing traffic from previous.

$$B_i = \sum_{i=1}^{N} v_i \qquad (9)$$

For reduction of required bit rate of links we need minimize load of packet headers. Especially this is actually for real time application – VoIP. In some configuration headers size is twice the size of the payload. When generating voice packets every 20 milliseconds on a slow link, the header consumes a large portion of the bandwidth.

PLC links during short periods of time (thunderstorm, strong rain) could have high BER > 10^{-3}, but during the most part of operation time BER is < 10^{-6}. It means that we need to apply reliable techniques of header compression to avoid lose of synchronization between compressor and decompressor during period with high BER.

Two conceptions of header compression application in the relation to pPLC link could be suggested:

- “Internal headers compression **IHC**”.
- “External headers compression **EHC**”.

EHC is provided by network equipment such as routers and based on application of Enhanced Compressed RTP (ECRTP) (RFC 3545) - technique for voice applications and IP headers compression (RFC 2507) for data applications.

IHC should be implemented inside of pPLC equipment functionality and based on application of Robust Header Compression v2 (RFC 4995, 5225) and Robust Header Compression TCP (ROHC-TCP) RFC 4996 .

Both concepts for mandatory types of traffic processing are shown in Fig. 11, 12. Miscellaneous types of traffic should be processed in the same way depends on using protocols.

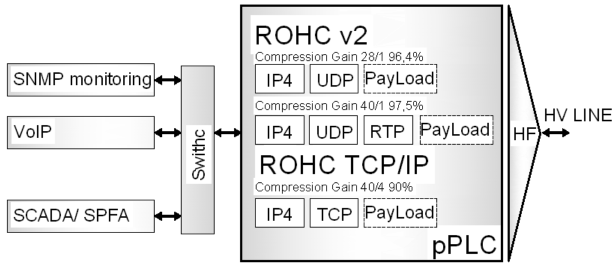

Fig. 11 Concept of IHC

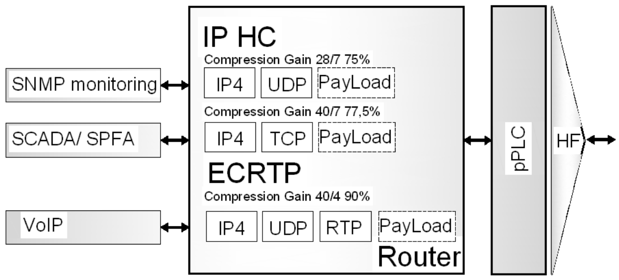

Fig. 12 Concept of EHC

For voice packets ROHC v2 provides header compression minimum to 1 byte, when ECRTP provides minimum value of 4 bytes. ROHC v2 was developed with wireless links as the main target, and introduced new compression mechanisms with the primary objective to achieve the combination of robustness against packet loss and maximal compression efficiency [8] ROHC v2 improves disadvantages of ROHC in the relation to packet reordering.

Enhanced Compressed RTP is improved CRTP technique described in RFC 3095. ECRTP was developed to overcome the problems of CRTP. CRTP does not perform well over links with long round trip time that lose and reorder packets. ECRTP extends CRTP by repeating context updates and by sending absolute values along with delta values when encoding monotonically increasing header fields to increase robustness. It inserts a header checksum when UDP checksum is missing, to improve error recovery and fail checks for the compression.

IPHC technique mostly suitable for modem links with low BER and packet loss rate. Performance of this technique for pPLC links during peaks of high BER is not guaranteed.

ROHC v2 has better performance characteristics than ECRTP in the relation to failure rate during packet loss, compression ration during packet loss, and same in relation to failure rate during packet reordering. But from implementation point of view EHC is simpler than IHC because algorithms of EHC are implemented in routers which have wide spread occurrence on the market of telecommunication equipment. IHC functionality should be implemented inside PLC terminal by manufacturer. IHC makes functionality of PLC more difficult and sufficiently increase its price.

Additional argument for benefit of EHC is robustness to loss of synchronization because of voice automatic detection (VAD) technique application. [9].

VI. Characteristics of Traffic Transmission, Required Bandwidth for Multi – Segment pPLC Link

As mentioned before for multi – segment pPLC links summary traffic of each further link is its own traffic and traffic from all previous nodes.

Traffic from one node could be derived as:

$$B_{SUM} = B_{DV} + B_{SCADA} + B_{SPFA} + B_{SNMP} + B_{MISC} \quad (10)$$

Where:
B_{DV} – dispatching voice channel;
B_{SCADA} – data from SCADA system;
B_{SPFA} – data from SPFA system;
B_{SNMP} – data from SNMP monitoring;
B_{MISC} – other types of traffic;

Table V contents the data concerning required bit rate for transmission different types of traffic for 110 kV Substation.

Thereby minimum required bit rate of one segment link on the assumption of G.729 application with ECRTP and VAD, and SNMP for 5 terminals is equal to 34 kbps.

For multi-segment link bit rate for subsequent segment must not be two times more. We could apply flexible algorithms of poling adjustment for SPFA system and adjust some delay to avoid simultaneous transmission. Also dispatching voice channels do not use simultaneously with all substations. Typically during operation process one dispatcher talk only with one substation and conferences do not use as a rule.

Bit rate of the nearest to the dispatching centre link could be derived with equitation (9).

Assume that SCADA traffic from each substation nearly has same bit rate. Equation does not include bit rate increasing because of changes in compressed headers in each intermediate node.

$$B_{LS} = B_{DV} + \sum_{1}^{N} B_{i(SCADA)} + B_{SPFA} + B_{SNMP} + B_{MISC} \quad (11)$$

Diagram in Fig. 13 shows dependence between minimum required bit rate *B* and number of nodes *N* for multi – segment link.

TABLE V
Types of Information Transmitted between Substations and Dispatching Centre

Traffic	Bit rate, kbps for one channel			
VoIP dispatching channels/ technological channels	Full rate	ECRTP	VAD	ECRTP+VAD
Codec G.729 (20 byte)	26,4	11,2	17,2	7,3
Codec G.723.1 (6,3 kbps , 30 byte)	18,4	8,4	12,0	5,5
SCADA	depends on number of signals, average 14,4 for $T_D < 3000$ MS.			
SPFA	9,6			
SNMP	0,8 kbps for one terminal			
E-mail, Internet	If recourses are available, maximum B_{SUM} if services are “in silence”			

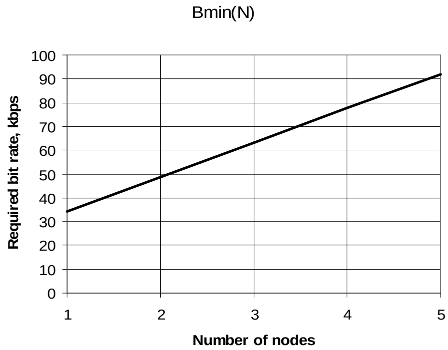

Fig. 13 Dependence between minimal required bit rate and number of nodes in multi-segment link

We observe number of nodes equal 5 because of time delay limitation for voice packets. According to ITU-T G.114 maximal value of time delay could be accepted equal 400 ms. Average time delay for voice packet transmission could be derived as:

$$T_A = T_{coder} + T_{frame} + T_{link} + T_{node} + T_{buffer} + T_{decoder} \quad (12)$$

Where:
T_{codec} – delay in codec;
T_{frame} – delay through frame generation;
T_{link} – delay through of data processing in PLC and transmission signals over HV line;
T_{node} – delay through of data processing in network equipment (router);
T_{buffer} – delay in jitter buffer;
$T_{decoder}$ – delay in decoder.

We need minimize time delay to provide maximal number of transit nodes in multi-segment link.

Duration of voice frame and delay in coder and decoder should be minimal. The most suitable type of voice codec is G.729 B with supporting of VAD algorithm. Default voice payload in frame is 20 ms, therefore time delay in coder and decoder is 25 ms.

Time delay in PLC link depends on performance of equipment – how fast terminal could process the data and prepare HF signal on the transmission side and make back conversion on the receiver. Time of signal propagation over HV line is not considered as too short. For modern PLC terminals latency of data process is 20-25 ms per terminal.

Time delay in node (router) depends on serialization delay T_{serial}:

$$T_{serial} = \frac{L}{B} \qquad (13)$$

Where:
L– frame size, bit;
B – link bandwidth, bps.

For link with bit rate equal 34 kbps T_{serial} is approximately 15 ms. Delay in jitter buffer depends on number of packet buffered packets. Assume that we process 2 frames and T_{buffer} is equal 40 ms.

Diagram of dependence between summary time of delay and number of nodes in multi – segment link is shown in Fig. 14.

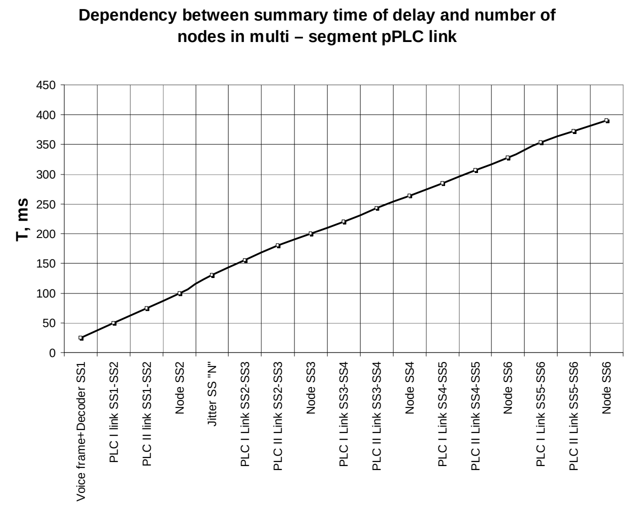

Fig. 14 Dependence between summary time of delay and number of nodes in multi – segment link

Calculation shows that maximal acceptable number of transit segment of pPLC link could not be more than 5.

VII. Conclusion

The main resumes of the exploration:

- Place of convergent pPLC links in the enterprise network of Energy Companies was defined. PPLC links could be used as back-up channels or for creating small networks where number of hops in multi – segment links is not more than 5.
- Minimal required bit rate for hops of multi - segment link was defined. Minimal bit rate for one – segment link is 34 kbps.
- Two schemes of packet headers compression in relation to application with pPLC links were suggested. IHC – with application of RFC 4995, 4996, 5225 and EHC – with application of RFC 2507 and 3545;
- Typical lengths and voltage class of HV lines where application of pPLC is mostly suitable were defined. These lines are 35 and 110 kV with length < 150 km.

The results of exploration show us that convergent packet PLC links can be very useful in the construction of small packet networks between substations in remote locations, such as deposits or low populated areas.

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