Structural optimization of Long Ethernet lines for use in automation systems of smart city and smart home

Andrey Semenov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia
E-mail: andre62.55@mail.ru

Abstract. The possibility of structural optimization of the telecommunications part of the telecommunication lines of the Long Ethernet network interfaces for servicing sensors and actuating elements of automation systems of a smart city and a smart home has been considered. A model of the analyzed structure has been introduced. Given the long distances and relatively low data exchange rates, the model involves the use of standard remote power supply equipment and multiplexing of signals from sensors and actuators. The method of estimating the lengths of separate segments of a mixed path is offered, and expediency of increase in length of a path for transmission of the multiplexed signals is shown.

1. Introduction
The practical implementation of the Smart City and Smart Home concept is based on the use of a large number of sensors of various physical quantities and actuator components. Sensors are used to collect data on the actual values of controlled parameters of the object, while the actuator components are designed to change them in the right direction with commands, which are formed by process controllers and other computer facilities [1 - 2].

Based on the convenience of building up such systems, they are usually implemented according to a hierarchical scheme, and at each level for increasing overall efficiency, additional sublevels can be applied. The structuring of the lowest level with most numerous connection points into sublevels is done mainly for the purpose of minimizing the total solution cost.

Radio transmission channels and cable communication lines can be applied for organizing data exchange in practically implemented and designed systems. Radio transmission channels due to their relatively low productivity, sensitivity to interference, ease of interception and unauthorized interference can be used in a limited number of cases in the operation of the system. Cable telecommunication lines that are free from such shortcomings, may be built in different ways.

As we go forward, we restrict ourselves to considering only one option for their implementation on the basis of Ethernet network interfaces operating with the help of twisted pair cables, which have become pretty widespread in that section of the system being created that directly interacts with terminal equipment. When creating such systems, due to the large number of serviced terminal devices, close attention is paid to reducing the costs required to implement the lower level. Given the fixed number of terminal devices being discussed, such an optimization can only be effectively
accomplished by appropriate construction of the linear section of the system. The main techniques that are involved in performing this procedure are:

- multiplexing,
- linear section wire optimization.

The optimization of the lower levels of information systems based on cable technology is considered in a number of works in relation to office buildings. The need for a separate analysis of automation systems is based on the fact that the provisions of well-known sources do not take into account the significant features of the smart city automation systems. Relative costs are used as a criterion of optimality of the structure being created.

2. Applied model

The functions of the study subject are performed by a two-level model, whose structural diagram is shown in Figure 1 and which provides for:

- the multiplexing of the transmitted signal at the upper sublevel (indicated by symbol A in the diagram);
- remote power supply of terminal equipment.

It is assumed that the work is carried out at a speed not exceeding 100 Mb/s, which is enough even for the most demanding surveillance systems in terms of bandwidth.

![Figure 1. System structure](image)

The series type connection of individual segments is accepted, which allows to obtain a greater length of the cable channel in comparison with daisy chain structures. Less functional flexibility of the structure Figure 1 is considered to be insignificant due to the small number of terminal devices in one branch.

The maximum lengths of A and B channels are not limited to the value of 100 m, which are specified for the information wiring horizontal subsystem of office information systems by ISO/IEC 11801 standards. Refusal to comply with this restriction is due to the fact that the structure in question is not initially subject to certification and warranty support of the manufacturer at the system level.

Given the static nature of the information system configuration to be under consideration, it is accepted that its linear section is built according to the Direct Connection scheme in section A and End to End (E2E) in section B. This makes it possible to avoid further accounting for the influence of cords and connectors at the engineering level.
Maximum length of sections A and B in the diagram Figure 1 is theoretically restricted to two main factors:

- probability of an error that is recorded in the IEEE802.3u specifications;
- restrictions of PoE remote power technology, which are set by IEEE802.3af standards.

It is known that the second restriction is more stringent (the interface automatically stops data transfer when the daisy resistance is exceeded). Based on this fact, the analysis is based on this feature.

The multiplexing coefficient is set equal to 1:3, which is a typical value for switches with remote power supply using PoE technology [4]. The power of the switch is set to 3.5 W.

Television cameras with a power consumption of 2.8 W (class I devices according to 802.3af) are applied as terminal devices [5].

3. Mathematical statement of the problem

Switch Figure 1 acts as a repeater in the structure and provides complete isolation of segments A and B from each other. Based on Ohm’s law for a chain section

$$RI + P/1 - E = 0,$$

where $P$ – the power of the powered equipment; $R = R_{el}/2$ , $R_{el}$ – loop back daisy resistance with the length of $L$ ($L = A$ or $L = B$ depending on the selected segment of the full channel), $P$ – receiver power.

Accepted that entering (1) source voltage output $E = 44$ V. In fact, most modern PoE devices provide $E = 48$ V output. The existing 10 percent difference is considered to be a calculation margin.

There are two restrictions applied to the lengths of individual paths and the entire system.

$$A, B < L_{max}, \text{ where } L_{max} - \text{ ultimate channel length}.$$

$$A + B = const.$$

It is necessary to find the quantities A and B at which

$$S_A + 3S_B \to \min,$$

where $S_A, S_B = 1$ – relative cost of lines A and B of the structure Figure 1.

4. Solution method

Equation (1) is a quadratic one and can be solved in quadratures. However, the result obtained in this case is poorly suitable for analysis and inconvenient for carrying out engineering calculations.

In order to eliminate this drawback, we take advantage of the fact that for typical values of PoE for modern technology and defined by IEEE802.2af/IEEE802.2at standards, we have

$$\frac{\partial F(I)}{\partial I} = R - P/1^2 >> 1,$$

where $F(I)$ – the left part (1). This feature allows us to use Newton’s
iterative method for solving (1). The number of iterations is restricted to one, because in the whole range of possible changes of parameters and variables included in (1), it is true that

$$RI \ll \frac{P}{E}. \quad (2)$$

Given the restrictions (2), it is advisable to adopt the following as a zero approximation $I_0 = \frac{P}{E}$. Then $F(I_0) = R \cdot \frac{P}{E}$, and $\frac{d}{dl} F(I_0) = R - \frac{E^2}{P}$, after that $I_1 = \frac{P}{E} \left(1 - \frac{1}{1 - E^2 / RP}\right)$. In addition, it’s useful to consider that $E^2 / RP \gg 1$. This feature allows for the application of known asymptotics $(1 + \xi)^n \approx 1 + \mu \xi$ and further simplify the end result by reducing it to an expression.

$$I = \frac{P}{E} \left(1 + \frac{RP}{E^2}\right). \quad (3)$$

For segment A of the structure Figure 1 the power is taken into account when setting $P$

- consumed by three TV cameras;
- scattering on the three line cables;
- PoE switch consumption.

Calculations show that the error of determining $I$ for (3) does not exceed 4%.

The resistance to direct current of a single twisted pair core is $R = \rho \frac{k_u L}{0.25 \pi D^2}$, where $\rho$ – copper resistivity, $k_u \approx 1$ – twisting contraction factor numerically equal to the length ratio of the twisted pair wire and cable. For typical constructions of 5e category $k_u \approx 1.05 - 1.08$.

For category 5e cables, we have $D = 0.52$ mm and, in the case of a conductor made of pure electrotechnical copper, the maximum value allowed by the standards is $R_{\text{max}} = 20$ Ohm that is achieved at the values $L_{\text{max}} = 170$ m. Transition to structures with increased core diameter allows increasing the value of this parameter, which is shown in Table 1.

Table 1. Limit length of cable line depending on core diameter

| Core diameter, mm | 0.52 | 0.55 | 0.57 | 0.60 | 0.64 |
|-------------------|------|------|------|------|------|
| L, m              | 170  | 190  | 204  | 226  | 257  |

5. Results analysis

In terms of increments on the basis of (3) under the additional condition, $I = \text{const}$ it is true that

$$I = \frac{P}{E} \left(1 + \frac{R(1 + \delta)P(1 + \varepsilon)}{E^2}\right), \quad (4)$$

where $\delta, \varepsilon$ – small parameters. After simplifying, taking into account (3) we obtain

$$\varepsilon \approx -\frac{RP}{E^2} \left(1 + \frac{RP}{E^2}\right)^{-1} \cdot \delta. \quad (5)$$

A minus sign in (5) indicates that the R and P parameters have an equal influence on the segment limit length.
In case of typical for POE equipment values of parameters R, P and E, it is true that \( \frac{RP}{E^2} \approx 0.1 \), i.e. daisy resistance reduction efficiency is approximately an order of magnitude lower than the power consumption reduction.

The provision of preference for power reduction is only valid at high power \( P \) values, which becomes the main means of reducing the current \( I \). In the case of class 1 devices application with consumption power not exceeding 4 W, the situation changes to the opposite. There is an effect that by increasing the diameter of the core to 0.64 mm, R can be reduced almost two-fold, while P power can be reduced by only 10–15 %.

It follows from formula (5), that all other conditions being equal, it is necessary to maximize the value of A with a comprehensive reduction of P. From (1), it follows in this case

\[
L = \frac{1}{R_iI}(E - \frac{P}{I}),
\]

where \( R_i \) – resistance of a twisted pair core of a single length.

6. **Estimation of costs for realization of the linear section of the system**

When building up a linear section of the structure, Figure 1, it makes sense to use already known equipment, development of new designs at the present stage of development of equipment is inexpedient. Standard ISO/IEC 11801 provides for the possibility of using several different designs. By default, the scope of application of this equipment implies a normal electromagnetic environment, which makes the use of shielded cable structures in any form of their implementation to be useless. Due to this fact, we will work with U/UTP constructions in the future [6].

The relative cost of 5e category 4-pair cable with a core diameter of 0.52 mm is taken as a unit. The cable sheathing material is selected according to the operating conditions. The structure itself is depicted on the left side, Figure 3.

![U/UTP cable cross section and structure of raw costs for its sale](image)

**Figure 3.** U/UTP cable cross section and structure of raw costs for its sale

Cable manufacturing is a highly mechanized production with a minimum amount of manual labor. This allows the cost of raw materials to be used as a measure of its design price. The cost structure of the 4-pair cable is presented on the right side, Figure 3. The cost of installation work is usually calculated based on the cost of a cable meter. Due to these features, the data in Table 2 is valid with respect to the relative cost per unit length of cables with different core diameters.

From (5), taking into account the definition of the value \( R = R_{dc} / 2 \), it follows that the increment of the length is inversely proportional to the daisy resistance. Thus, the transition to a cable with a large core diameter gives an increase in length. In case of a fixed communication range due to the lower cost of the line as a whole, this feature allows reducing the cost of implementing the whole system.
Table 2. The relative cost of path length unit depending on the core diameter

| Core diameter, mm | 0.52 | 0.55 | 0.57 | 0.60 | 0.64 |
|-------------------|------|------|------|------|------|
| S, m              | 1    | 1.12 | 1.20 | 1.33 | 1.51 |

The value of the gain achieved at the system level is shown in Table 3. As a numerical measure of the total relative cost of the linear section of the structure Figure 1 and a gain, accordingly, an aggregate of the form was used

\[ G = 3S_p \frac{L_p}{170} + S_A \frac{L_A}{170}. \]

Where \( S_A, S_p \) – unit cost of cables for the implementation of segments A and B.

Table 3. Estimation of the relative cost gain when transition to a cable with an increased core diameter with a path length of 340 m

| Core diameter, mm | 0.52 | 0.55 | 0.57 | 0.60 | 0.64 |
|-------------------|------|------|------|------|------|
| segment A 4-pair cable |
| A, m              | 170  | 190  | 204  | 226  | 260  |
| B, m              | 170  | 150  | 136  | 114  | 80   |
| S                 | 4    | 3.90 | 3.84 | 3.78 | 3.75 |
| segment A 2-pair cable |
| A, m              | 170  | 190  | 204  | 226  | 260  |
| B, m              | 170  | 150  | 136  | 114  | 80   |
| S                 | 3.5  | 3.27 | 3.12 | 2.89 | 2.60 |

Approximately 6\% of the value gain can be significantly improved by transition to specialized 2-pair structures, originally intended for the construction of Long Ethernet cable channel. In this case, it increases to 35\%. Their use is advisable because of the smaller cross-section, which demonstrates the simplicity of laying due to greater flexibility.

Figure 4. Comparison of cables with different numbers of twisted pairs

In addition, we note that the transition in the linear section to specialized designs with an increased core diameter allows increasing the maximum path length to 500 m without reducing the automation system functionality.
7. Conclusions

1. It is advisable to build the lower levels of smart city automation systems in the form of an initially agreed single complex of active and passive equipment.
2. The main means of structural optimization are multiplexing technology and twisted pair cables with an increased conductive core diameter.
3. When building up the system, it is advisable to increase the length of the cable of that section along which the multiplexed signal is transmitted.
4. The total extension range of the terminal device can reach 500 m without the use of specialized active equipment.

References

[1] Volkov A A 2017 Industrial and civil engineering 9 4
[2] Volkov A A 2019 Industrial and civil engineering 9 6
[3] Stefanova N A 2018 Current issues of the modern economy 4 175
[4] Semenov A B 2017 LAN 10 28
[5] Chelyshkov P D, Semenov A B 2019 Vestnik svjazi 2 4
[6] Semenov A B 2019 Last mile 3 32