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BASE STATION POWER BACKUP SCHEDULING FOR NETWORK PROVIDERS BY A THREE-PERSON DYADIC GAME

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Background. Recently reliable telecommunication has been challenged due to power grid instability and temporary blackouts. There is a strong need for optimizing the base station power backup for telecommunication network providers.

Objective. The purpose of the paper is to substantiate a game model of optimizing the base station power backup for three major telecommunication network providers and determine the best strategy. The optimization is based on payoff symmetry, rather than equilibrium.

Methods. There are only two pure strategies at the provider — to apply the power backup or ignore applying, whenever needed. The latter means avoiding additional expenses for the provider while applying the power backup requires additional expenses. The cost of applying the power backup is set to a conditional unit. It is further assumed that, if only one provider does not apply the power backup, it does not affect the quality of service (QoS). When there is no backup at all, QoS worsens significantly, users subsequently seek for alternative telecommunication services, and shortly every provider loses the 3 units.

Results. The provider's expected payoff, being treated as a loss, is minimized over the set of symmetric mixed situations, where the provider's mixed strategy is the no-backup probability. The base station power backup best strategy is realized by turning the power backup off with an irrational probability whose value lies between 0.05904144 and 0.05904145. It is more likely that the backup state switch is possible at definite time intervals usually counted in hours or days.

Conclusions. The best strategy allows saving the power backup for 5.904 % of the temporarily-off-the-grid period by saving 2.9 % of expenses for the backup, which does not worsen the QoS. Whenever the amounts of providers' expenses, costs, and losses are changed, the best strategy is determined in the same way it has been found.

Keywords: *power backup; network providers; QoS; three-person dyadic game; best symmetric situation; scheduling.*

1. Introduction

Recently reliable telecommunication has been challenged due to power grid instability and temporary blackouts. Network providers started working on testing and applying new technologies and approaches to maintain the same satisfactory quality of service (QoS), which is essential to keep the market sustainability, profit, attractiveness, and possibility for future investments [1], [2]. An example is the internal roaming supported by Ukrainian cellular operators since 2022 [3]. Another example is power backup provided for some base stations to continue functioning while being temporarily off the grid [4]. Obviously, such a backup is relatively expensive, especially if it should work for a few hours, so only selected base stations may have non-grid power [5]. This results in fluctuations in link rate, non-smooth connectivity, and the eventual worsening of QoS [6], [7]. Further aftermath is a potential loss of users (or subscribers, customers), which basically is the main feature of declination of the provider [8], [9]. Therefore, there is a strong need to optimize the base station power backup for telecommunication network providers.

2. Objective

The above-described problem refers to the allocation of limited resources [10]. Due to network providers being reluctant to cooperate, the problem is modelled by non-cooperative games [11]. The objective is to substantiate a game model of optimizing the base station power backup for three major telecommunication network providers and determine the best strategy. First, a set of possible primitive (pure, using the game theory terminology) strategies of the provider is to be constituted. Second, the game payoffs of the providers are assumed. Then the game model is to be presented and substantiated. Next, the best strategy for the base station power backup will be determined. Finally, the result is to be discussed and a conclusion with an outlook for further research will be made.

3. Primitive strategies

The set of possible primitive strategies of the network provider should be constituted as simple as possible. Therefore, there are only two pure strategies at the provider — to apply the power backup or ignore applying, whenever needed. The latter means avoiding additional expenses for the provider, while users are not charged with new, slightly inflated, tariffs. Applying the power backup, on the contrary, requires additional expenses, which may be partly imposed on users via subsequently updated charges [12].

Let the power backup application be a pure strategy of value 0. Alternatively, let the no-backup strategy have a value of 1. Denote the pure strategies of the three providers by x, y, z. So,

$$x \in \{0, 1\},\ y \in \{0, 1\},\ z \in \{0, 1\}.$$

Triple $\{x, y, z\}$ is a pure strategy situation in a dyadic non-cooperative game

$$\left\langle \{0, 1\}, \{0, 1\}, \{0, 1\}, \left\{ L_1(x, y, z), L_2(x, y, z), L_3(x, y, z) \right\} \right\rangle, \tag{1}$$

in which

$$L_1(x, y, z),\ L_2(x, y, z),\ L_3(x, y, z) \tag{2}$$

are the payoff functions of the first, second, and third providers, respectively. Payoffs (2) are overall conditional losses (costs, additional expenses, reimbursements) of the providers, which must be minimized.

4. Game payoffs

It is easy to see that there are eight pure strategy situations in game (1). Obviously, solutions and, generally speaking, solvability of game (1) depend on payoff functions (2) of the providers. It is fairly assumed that these functions have the same value in any symmetric pure strategy situation, i. e. equalities

$$L_1(0, 0, 0) = L_2(0, 0, 0) = L_3(0, 0, 0)$$

and

$$L_1(1, 1, 1) = L_2(1, 1, 1) = L_3(1, 1, 1)$$

hold. In a first approximation, the values of payoff functions (2) can be defined using the conception of the well-known model of environmental protection [13], [14]. The cost of applying the power backup is set to a conditional unit. Thus, when every provider applies the power backup,

$$L_1(0, 0, 0) = L_2(0, 0, 0) = L_3(0, 0, 0) = 1.$$

When there is no backup at all, internal roaming performs poorly, QoS worsens significantly, users subsequently seek alternative telecommunication services, and shortly every provider loses the 3 units:

$$L_1(1, 1, 1) = L_2(1, 1, 1) = L_3(1, 1, 1) = 3.$$

It is further assumed that, if only one provider does not apply the power backup, it does not affect QoS. Two or more providers without power backups deteriorate QoS significantly resulting in losing the 3 units. So, if a provider applies the power backup while the other two do not apply, the provider loses 4 units.

The game payoffs are easier to present visually using the cube of mixed strategy situations [13], [15]. Owing to this is a dyadic game, a mixed strategy of a provider can be represented by just a probability of selecting a pure strategy. For definiteness, let it be the no-backup strategy. Denote the mixed strategy of the first, second, and third providers by p, q, r, respectively. Herein, e. g., p is a probability that the first provider does not apply the power backup (whether the provider does not have it or it is just turned off). Therefore,

$$1 - p,\ 1 - q,\ 1 - r$$

are the probabilities of that the providers apply the power backup. Fig. 1 shows the cube (originally presented with negative payoffs to be maximized in [15]), at whose vertices the game payoffs are also shown.

Although the question of the 3 units seems to be openly discussible, it is straightforwardly adopted from [15] to simplify the first approximation. Besides, it is shown below that this amount can be changed without affecting the way through which the best strategy is determined.

5. Dyadic game model

In dyadic game (1) the i-th provider's expected payoff in situation $\{p, q, r\}$ is calculated as follows [15]:

$$\begin{aligned} l_i(p, q, r) = {} & (1-p)(1-q)(1-r) L_i(0, 0, 0) + \\ & + (1-p)(1-q) r L_i(0, 0, 1) + \\ & + (1-p) q (1-r) L_i(0, 1, 0) + (1-p) q r L_i(0, 1, 1) + \\ & + p(1-q)(1-r) L_i(1, 0, 0) + p(1-q) r L_i(1, 0, 1) + \\ & + pq(1-r) L_i(1, 1, 0) + pqr L_i(1, 1, 1) \text{ for } i = \overline{1, 3}. \end{aligned} \tag{3}$$

It was shown in [13], and [15] that dyadic game (1) has four equilibria in pure strategies

$$\{0, 0, 1\}, \tag{4}$$

$$\{0, 1, 0\}, \tag{5}$$

$$\{1, 0, 0\}, \tag{6}$$

$$\{1, 1, 1\} \tag{7}$$

and five equilibria in mixed strategies

$$\left\{0, \frac{1}{3}, \frac{1}{3}\right\}, \quad (8)$$

$$\left\{\frac{1}{3}, \frac{1}{3}, 0\right\}, \quad (9)$$

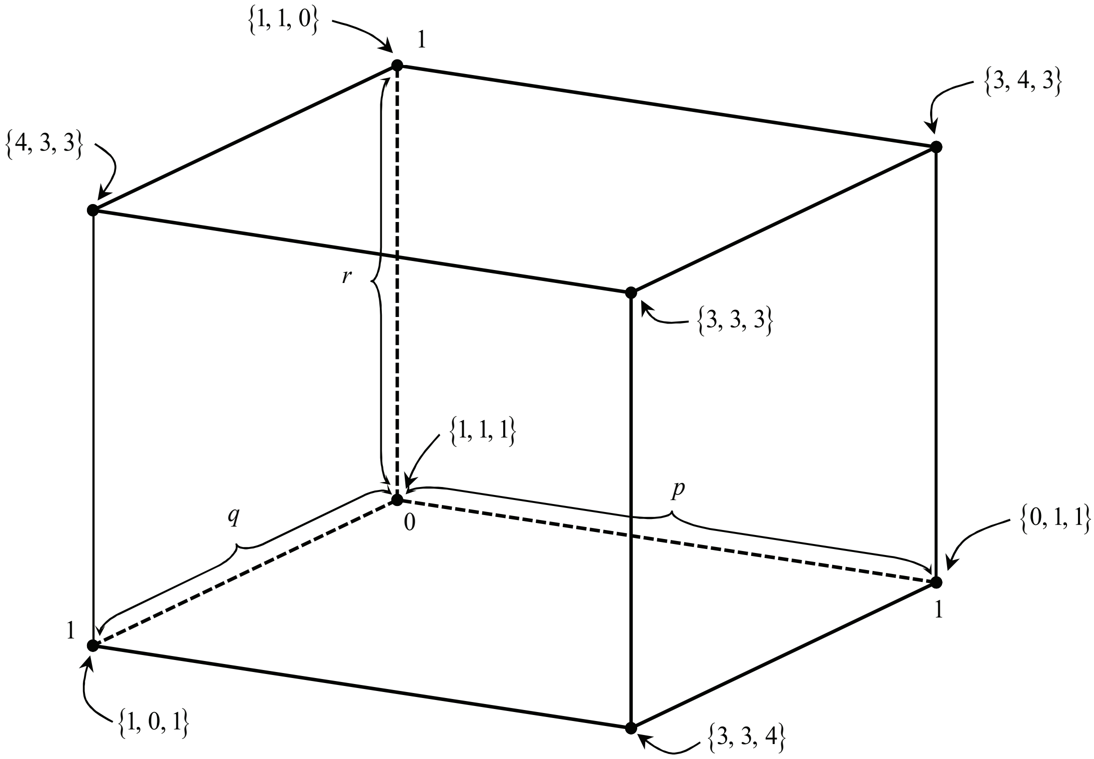

Fig. 1. The cube of all (mixed strategy) situations in dyadic game (1) whose payoffs are conditional units of losses

$$\left\{\frac{1}{3}, 0, \frac{1}{3}\right\}, \quad (10)$$

$$\left\{\frac{3-\sqrt{3}}{6}, \frac{3-\sqrt{3}}{6}, \frac{3-\sqrt{3}}{6}\right\}, \quad (11)$$

$$\left\{\frac{3+\sqrt{3}}{6}, \frac{3+\sqrt{3}}{6}, \frac{3+\sqrt{3}}{6}\right\}. \quad (12)$$

Pure strategy equilibria (4) — (6) are non-symmetric, and in those situations, two providers apply the power backup as opposed to a no-backup provider. Although the summed losses are 2 (see the vertices of the cube in Fig. 1), which is $\frac{2}{3}$ per provider, non-symmetric equilibria (4) — (6) are quite unstable and eventually their equilibrium property would vanish [16], [17]. Equilibrium situation (7) means no-backups at all, which is at least economically unacceptable due to high losses in the 3 units per provider.

Mixed strategy equilibria (8) — (10) are non-symmetric as well, and in those situations only one provider constantly applies the power backup as opposed to the other two providers applying just two thirds of theirs backups (because probability $\frac{1}{3}$ means partial no-backup strategy, e. g., by not applying the power backup for one-third of the temporarily-off-the-grid period). In addition to the non-symmetry leading to instability, the respective payoffs in equilibria (8) — (10)

$$\left\{l_1\left(0, \frac{1}{3}, \frac{1}{3}\right), l_2\left(0, \frac{1}{3}, \frac{1}{3}\right), l_3\left(0, \frac{1}{3}, \frac{1}{3}\right)\right\} = \left\{\frac{4}{3}, 1, 1\right\},$$

$$\left\{l_1\left(\frac{1}{3}, \frac{1}{3}, 0\right), l_2\left(\frac{1}{3}, \frac{1}{3}, 0\right), l_3\left(\frac{1}{3}, \frac{1}{3}, 0\right)\right\} = \left\{1, 1, \frac{4}{3}\right\},$$

$$\left\{l_1\left(\frac{1}{3}, 0, \frac{1}{3}\right), l_2\left(\frac{1}{3}, 0, \frac{1}{3}\right), l_3\left(\frac{1}{3}, 0, \frac{1}{3}\right)\right\} = \left\{1, \frac{4}{3}, 1\right\}$$

are even more depressive and unstable than those in pure strategy equilibria (4) — (6).

Mixed strategy equilibria (11) and (12) are symmetric, so their payoffs are identical. In equilibrium situation (11) each provider loses $2-\frac{\sqrt{3}}{2}$ conditional units, whereas in equilibrium situation (12) each provider loses $2+\frac{\sqrt{3}}{2}$ conditional units. Inasmuch as

$$2+\frac{\sqrt{3}}{2} > 2-\frac{\sqrt{3}}{2} > 1.133974,$$

equilibrium (12) is not considered further along with unstable and unprofitable equilibria (4) — (10). However, equilibrium situation (11) is unprofitable compared to non-equilibrium situation $\{0, 0, 0\}$, in which every provider applies the power backup. The amount of 0.133975 conditional units can be called an additional cost of reaching an equilibrium. However, this tradeoff does not make much sense due to the following two reasons. First, even by not applying the power backup for about one-fifth of the temporarily-off-the-grid period, the provider pays more than by fully applying the power backup. Second, probability

$$\frac{3-\sqrt{3}}{6} = \frac{1}{2} - \frac{\sqrt{3}}{6}$$

is irrational, so it cannot be practically realized through a finite number of game rounds. In other words, using mixed strategy (11) is statistically inconsistent to reach practically equal losses of $2-\frac{\sqrt{3}}{2}$ conditional units per provider, whichever the dyadic game is (finitely repeatable or, all the more, possibly repeatable with fewer game rounds). Therefore, situation (11) is unacceptable also, being the best one so far, though.

6. Best strategy

Inasmuch as none of equilibrium strategies is acceptable due to instability and unprofitability, the best strategy should be determined from the other point of view. It is about symmetry and equal profitability, rather than equilibrium. If a symmetric situation

$$\{p^*, q^*, r^*\} = \{\vartheta, \vartheta, \vartheta\} \tag{13}$$

exists such that the providers' expected payoffs in situation (13) are lesser (the payoff herein is the loss equivalent) than those in equilibrium situation (11) [15], then situation (13) is more profitable, where

$$l_i(\vartheta, \vartheta, \vartheta) < l_i\left(\frac{3-\sqrt{3}}{6}, \frac{3-\sqrt{3}}{6}, \frac{3-\sqrt{3}}{6}\right) = 2-\frac{\sqrt{3}}{2} \text{ for } i=\overline{1,3}. \tag{14}$$

In addition, if inequality

$$\vartheta < \frac{3-\sqrt{3}}{6} \tag{15}$$

holds along with inequality (14), this would imply providing more power backup and thus ensuring higher QoS. Nevertheless, if situation (13) turns out to be such that

$$l_i(\vartheta, \vartheta, \vartheta) < 1 \text{ for } i=\overline{1,3} \tag{16}$$

along with inequality (15), then this would be more profitable than a non-equilibrium situation $\{0, 0, 0\}$, in which every provider applies the power backup.

Using (3), the i-th provider's expected payoff in situation (13) is calculated as

$$l_i(\vartheta, \vartheta, \vartheta) = (1-\vartheta)^3 L_i(0,0,0) + \vartheta(1-\vartheta)^2 L_i(0,0,1) + \vartheta(1-\vartheta)^2 L_i(0,1,0) + \vartheta^2(1-\vartheta) L_i(0,1,1) + \vartheta(1-\vartheta)^2 L_i(1,0,0) + \vartheta^2(1-\vartheta) L_i(1,0,1) + \vartheta^2(1-\vartheta) L_i(1,1,0) + \vartheta^3 L_i(1,1,1) \text{ for } i=\overline{1,3},$$

which is simplified to

$$l_i(\vartheta, \vartheta, \vartheta) = -6\vartheta^3 + 9\vartheta^2 - \vartheta + 1. \tag{17}$$

Find extremum points of function (17), which does not depend on i. Its first derivative is

$$\frac{dl_i}{d\vartheta} = -18\vartheta^2 + 18\vartheta - 1 \tag{18}$$

and

$$-18\vartheta^2 + 18\vartheta - 1 = 0$$

if

$$\vartheta = \vartheta_1 = \frac{3-\sqrt{7}}{6} \tag{19}$$

or

$$\vartheta = \vartheta_2 = \frac{3+\sqrt{7}}{6} \tag{20}$$

where $\vartheta_1 \in (0;1)$, $\vartheta_2 \in (0;1)$, i. e. zeros (19) and (20) of first derivative (18) are probabilities. The second derivative of function (17) is

$$\frac{d^2 l_i}{d\vartheta^2} = -36\vartheta + 18,$$

where

$$\left.\frac{d^2 l_i}{d\vartheta^2}\right|_{\vartheta=\vartheta_1} = -36\vartheta_1 + 18 = 6\sqrt{7} > 0 \tag{21}$$

and

$$\left.\frac{d^2 l_i}{d\vartheta^2}\right|_{\vartheta=\vartheta_2} = -36\vartheta_2 + 18 = -6\sqrt{7} < 0. \tag{22}$$

Positive value (21) implies that (19) is the minimum point of function (17), whereas (22) is its maximum point. Therefore, the minimal payoff of the i-th provider in symmetric situation (13) is

$$l_i\left(\vartheta_1, \vartheta_1, \vartheta_1\right) = l_i\left(\frac{3-\sqrt{7}}{6}, \frac{3-\sqrt{7}}{6}, \frac{3-\sqrt{7}}{6}\right) =$$

$$= -6\vartheta_1^3 + 9\vartheta_1^2 - \vartheta_1 + 1 = 2 - \frac{7\sqrt{7}}{18}, \qquad (23)$$

where

$$0.05904 < \vartheta_1 = \frac{3-\sqrt{7}}{6} < 0.0590415$$

and

$$0.971096 < 2 - \frac{7\sqrt{7}}{18} < 0.971097 .$$

Consequently, the strategy of applying the power backup with probability

$$1 - \frac{3-\sqrt{7}}{6} = \frac{3+\sqrt{7}}{6},$$

where

$$0.94095 < \frac{3+\sqrt{7}}{6} < 0.94096 ,$$

is the best one for every provider. The best strategy allows saving the power backup for 5.904 % of the temporarily-off-the-grid period by saving 2.9 % of expenses for the backup, which does not worsen the QoS [18], [19].

7. Discussion and conclusion

It ought to be underlined that the conditional units of loss regard only permanent expenses. The costs of the power backup equipment and its mounting are intentionally not included because they are always present as a part of the telecommunication infrastructure development [20]. Expenses for turning on and off the power backups are assumed to be negligible and are not counted. Thus, the best strategy for the base station power backup is realized by turning the power backup off with probability $\vartheta_1 = \frac{3-\sqrt{7}}{6}$. It is more likely that the backup state switch is possible at definite time intervals (periods or units). The time unit is usually counted in hours or days.

Suppose that the providers are capable of switching their power backup states every three hours (this is a regular temporarily-off-the-grid period). Fig. 2

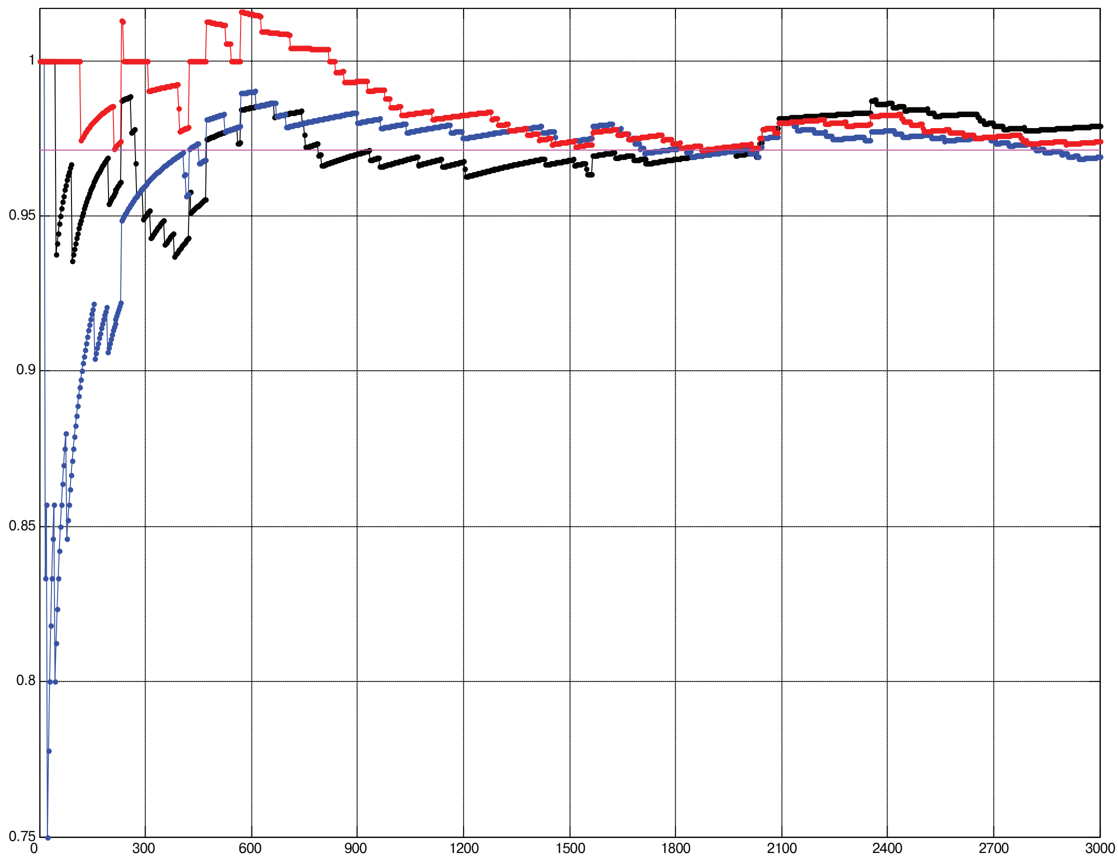

Fig. 2. The average loss of the provider using the best strategy versus the count of 3-hour interval

presents the polylines, each of which is the average loss of the provider using the best strategy via a computer simulation. It is clearly seen that, as time elapses, the average loss of every provider tends to optimal value (23) [11], [13], [15], [21]. Other similarly conducted computer simulations confirm (Fig. 3) that the conditional convergence interval in this set-up is about 125 days (which are 3000 hours), after which the average loss of the provider declines from optimal value (23) no more than by 2 %. This means that the result of using the best strategy yields in about 125 days.

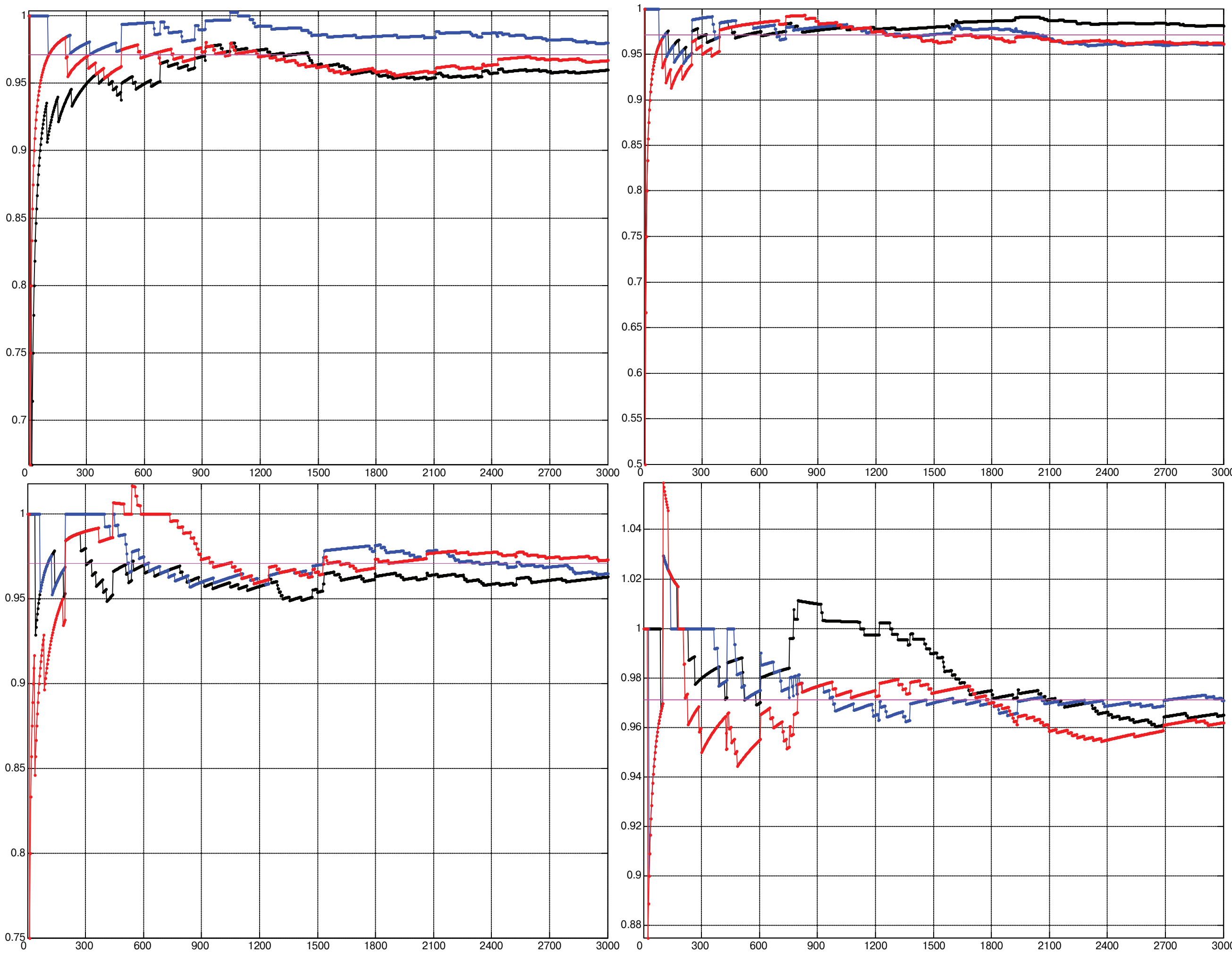

Fig. 3. The average loss polylines from the other computer simulations on the same time scale used in Fig. 2

The presented research utilizes the well-known 3-person dyadic game whose two dilemma-like strategies (back up the power supply or not) are sufficient to model real-world scenarios. The amounts of loss expressed in conditional units have been remained the same because it is impossible to assess permanent expenses under uncertainty of the temporarily-off-the-grid period duration and QoS degradation [6], [9]. Moreover, whenever the amounts are changed, the best strategy is determined in the same way it has been found for the cube in Fig. 1 starting from the principal inequality (16).

Determining limits within which the method of finding the best symmetric situation by minimizing the provider's expected payoff (aggregate losses, expenses, damage, fallout) in this situation is a matter of further research. This will allow loosening (varying to some extent) the provider's potential losses in conditional units (see the vertices of the cube in Fig. 1). The cube vertices as pure strategy situations with respective payoffs in Fig. 1 must be generalized.

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Романюк В.В.

Розклад забезпечення базових станцій резервним енергоживленням для мережевих провайдерів на основі діадичної гри трьох осіб

Проблематика. Останнім часом надійна телекомунікація була випробувана нестабільністю електричної мережі та тимчасовими вимкненнями. Існує серйозна потреба в оптимізації забезпечення базових станцій резервним енергоживленням для телекомунікаційних мережевих провайдерів.

Мета дослідження. Обґрунтувати ігрову модель оптимізації забезпечення базових станцій резервним енергоживленням для трьох великих телекомунікаційних мережевих провайдерів і визначити найкращу стратегію. Основою оптимізації є симетрія виплат, а не рівновага.

Методика реалізації. У провайдера є лише дві чисті стратегії — застосовувати резервне енергоживлення або ігнорувати його, коли у ньому постає потреба. Останнє для провайдера означає уникнення додаткових витрат, тоді як застосування резервного енергоживлення потребує додаткових витрат. Вартість застосування резервного енергоживлення прийнято рівною умовній одиниці. Далі припускається, що, за умови, коли лише один провайдер не застосовує резервне енергоживлення, це не впливає на якість обслуговування. Коли резервного енергоживлення немає взагалі, якість обслуговування значно погіршується, користувачі шукають альтернативні телекомунікаційні послуги, і невдовзі кожен провайдер втрачає 3 умовні одиниці.

Результати дослідження. Очікувана виплата провайдера, за яку покладено його втрати, мінімізується на множині симетричних змішаних ситуацій, де змішаною стратегією провайдера є імовірність вимкнення резервного енергоживлення. Найкраща стратегія забезпечення базової станції резервним енергоживленням реалізується вимкненням резервного енергоживлення з ірраціональною імовірністю, значення якої лежить між 0.05904144 та 0.05904145. Більш вірогідно, що зміна стану резервного енергоживлення можлива у визначені часові інтервали, якими зазвичай є години або дні.

Висновки. Найкраща стратегія дозволяє заощаджувати резервне енергоживлення на 5.904 % від періоду тимчасового відключення, що також заощаджує 2.9 % видатків на резервне енергоживлення, але при цьому не погіршує якість обслуговування. Коли суми видатків, вартостей та втрат провайдерів змінюються, найкраща стратегія визначається у той же спосіб.

Ключові слова: *резервне енергоживлення; мережеві провайдери; якість обслуговування; діадична гра трьох осіб; найкраща симетрична ситуація; розклад.*