A collaborative game theory approach for determining the feasibility of a shared AS blockchain infrastructure

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***Abstract*— The paper studies the feasibility of building a shared AS blockchain infrastructure employing a collaborative game theory approach. Game theory is used due to its versatility on analyzing situation where the outcome depends on the actions of several actors (AS) and on the estimated payoff when an actor makes a decision. The games chosen are in the category of Cooperative Game type, where multiple actors cooperate and form a coalition which they join or leave based upon their payoffs / reward. PFG is the basis of the algorithm implemented to demonstrate the feasibility of integrating a blockchain solution in an AS federation and to validate the reason for this integration. A mechanism of incentives is proposed to stimulate the cooperation of multiple AS.**

Keywords—game theory, blockchain, autonomous system, feasibility, federation

I. Introduction

The paper proposes to validate the feasibility of a collaborative approach in integrating a blockchain solution by a coalition / federation of autonomous systems (AS). The solution presented in this article simulates the evolution over time of a collaborative behavior and the benefits that result from this behavior in order to learn if it is more beneficial for an AS to collaborate or to act on its own. It uses game theory mathematical models to analyze the interactions between different AS in the context of blockchain technology. Several strategies and choices are modeled and compared, proving the feasibility of building a shared AS blockchain infrastructure

Game theory represents the mathematical model study of the strategical interaction between rational (at all times) agents (two or more) that take decisions in a situation that contains a set of rules and consequences [1] . Game theory is used for strategical behavior analysis, taking into account how the agents expect other participants to behave. This branch of applied mathematics provides means for analyzing situations where participants take interdependent decisions. This interdependence makes each participant to take into account the possible decisions and strategies that other participants might have in the process of forming its own strategy [2]. In this way, game theory can be used for finding the optimal gain based on the analysis of costs and benefits of each participant individually. This can be done exploring the gain in every possible situation over the course of actions that are benefic to each party that competes. These actions can be derived from the combinations of the simultaneous actions of the parties involved. A solution of such game describes the optimal decisions of the participants – which may have common interests, opposing interests or shared interests – and the consequences that result from these decisions.

Game theory contains a set of analytical means that aim to help understand the phenomenon observed by the interaction of agents who make decisions. It starts from the assumption that (rational) agents follow well-defined objectives and take into account the information / expectations they have about the behavior of other agents. It is assumed that all participants reason and act strategically. In such a game, each participant analyzes the possible reaction of the other participants to his action and only then makes a decision that will serve him best. Such an environment, in which the above-mentioned characteristic is mutually valid for all participants, is called strategic environment [3]. Due to its versatile nature, Game theory is used different field, ranging from economics, political science, sociology to computer science [4] (e.g., wireless networks [5], cybersecurity and cloud computing [6]).

Cooperative games within game theory are games in which "competition" occurs between groups (coalitions) of participants, due to the possibility and ability of participants to form cooperative behaviors [7]. This type of games can be classified as non-zero sum games. They are characterized by the fact that the profit of one participant does not necessarily mean the loss of another participant, and even in some conditions both participants can benefit from a situation. In these games - also called variable sum - the ability of the participants to cooperate and how this happens can have a significant influence on the end results. In contrast, in games with a constant sum, cooperation and communication do not make sense given that there is no possibility for more participants to have a gain. In the case of cooperative games. where participants share a common goal, the solution involves coordinating the decisions of the parties in the most efficient way [2].

A blockchain data structure is defined as an ordered, back-linked list of blocks of transactions [8]. A blockchain system is based on a peer-to-peer (P2P) network, which is a resilient, decentralized and open network. The system users are represented by the nodes in the network. All nodes are hierarchically equal, there are no special nodes, so they can both use services and provide them to others. At the same time, the nodes within the blockchain can have different roles, depending on the functionality they support.

For this paper the concept of federation of Autonomous Systems (AS federation) – ASs that collaborate for a common goal, was used. The AS federation aims to promote collaboration between ASs in the implementation of a blockchain over the networks of each AS. In general, a federation refers to a group of entities that adhere to and are committed to complying with and integrating a certain standard and operating in accordance with it. In the cooperation within the federation, the entities can have the freedom to comply and integrate the respective standard in their own way, customized to the internal needs and characteristics.

The AS that will choose to join the federation must be committed to integrating and implementing the blockchain solution within the networks they manage. In this way, a large space of interconnected networks can be obtained that integrate blockchain technology, thus resulting in a homogeneous environment within the federation. By integrating the blockchain, the AS in the federation will obtain a distributed environment to help them manage their infrastructure. The advantage of joining the federation is that an AS can choose to collaborate with other autonomous systems in the federation for implementing and integrating the blockchain, and in using its functionalities.

An AS can store its data in the blockchain in a secure manner, knowing that access is restricted. The blockchain ensures the integrity of the data provided by the AS, transparency, and the traceability.

The papers original contributions are:

- using game theory, a mathematical model was used to analyze the interactions between different autonomous systems (AS) in the context of blockchain technology;
- a PFG based algorithm and its payoff function were proposed and derived from the analyzed parameters;
- the feasibility of integrating a blockchain solution in a federation of ASs was demonstrated by comparing three game theory approaches.

The paper is organized as follows: Section II provides background and related work regarding blockchain and collaboration approaches in game theory. Section III presents and describes the proposed algorithm and the approach that this algorithm takes. The experimental results are presented and analyzed in section IV. Section V concludes the paper and presents possible further improvements.

II. Background

In a blockchain system, depending on the resources available for storage and verification, there are two types of nodes: full nodes and light nodes. Full nodes store locally the entire blockchain (and all block components) with all transactions and the nodes are involved in the complete verification of all transactions and blocks, based on the fixed rules set of the system. Accelerating blockchain search of full nodes using high performance computing (HPC) architectures such as graphics clusters that can offer the necessary power [9]. These nodes have both inbound and outbound connections with other users. Through the input connections all new transactions and blocks from other nodes are received, and they are checked according to a well-defined set of rules. Valid blocks and transactions are cached locally and sent to other complete nodes. Those that are found invalid are removed. Nodes that have storage and power constraints can operate without storing the entire blockchain and are called partial nodes. These nodes rely on the other nodes to obtain partial views of the relevant parts and to verify the transactions, downloading only the block headers, without including the transactions in the blocks [9]. A transaction is the smallest element within the blockchain and represents a data structure that encodes the transfer of information between participants. A certain value is transferred between users, thus changing the owner. The entire transfer history is stored in the blockchain, each transaction being a signed public entry. Once the transaction has been generated, it will be shared with the other nodes with which a connection is established. Full nodes validate the received transaction, propagate it further in the network and store it in the memory pool until it is verified and accepted within a block.

The games chosen are in the category of Cooperative Game type, where multiple actors cooperate and form a coalition which they join or leave based upon their payoffs / reward. In [10] the authors focus on the quote "I help you because you helped others" and based on this they propose a solution that promotes collaboration and a behavior that will shift away from the equilibrium state that the game prisoner's dilemma has - non-cooperation, everybody on its own. Game theory is used in cognitive networks in order to determine nodes to cooperate even though they have different goals and the nodes are selfish. In [11] an energy grid model is presented where the energy transfer is prioritized to be made inside of a formed coalition and just after no one from the coalition needs energy it can be made to the base station. Coalitional game theory is used for micro-grid distribution networks in order to improve collaboration. Here the behavior of collaborating and helping other members of coalition is enforced as a first step and just after this step other actions can be made.

In [12] the authors propose a PFG (pay-for-gain) mechanism for nodes in delay tolerant networks. The PFG mechanism helps the nodes collaborate to share their available buffer space in order to process and send messages and, at the same time, eliminates the ill behavior of nodes that use others buffer space for their own good but never help. The mechanism proposed in [12] was adapted and applied to demonstrate the feasibility of integrating a blockchain solution in an AS federation

III. Proposed solution

In [6] the authors present the characteristics of different cloud beneficiaries and their actions to gain a maximum financial advantage. Similar, in our proposed approach, the characteristics of blockchain systems and actors are presented and the financial advantages for an AS to adhere to a federation are discussed. Thus, the proposed algorithm and its payoff function is derived from the analyzed parameters.

A. Cost calculation model for hosting and maintaining a blockchain

In [13] the issue of anticipation and calculation of a blockchain solution is addressed. This issue is not easy to foresee due to the fact that the history of such implementations is recent and limited. Also, there are new proposals that come with improvements, or new implementations that don't help the mentioned issue because most of the time the approaches used are new and different. In this way, the authors define a way of cost calculation based on data that come from global clients for which proof of concepts, pilot versions or even production ones were implemented. Also, they used information from their internal platform.

Based on the analysis made on the presented data, the conclusion is that the minimum requirement for hosting a blockchain is to have 10 (full) nodes and 250 users. For the number of transactions (transaction volume), the amount differs in regard to the solution application from a couple thousands to millions of transactions per year. However, the most blockchain solutions fall in the category that has a transaction volume of around 365 000 transactions per year (1000 transactions per day). The same can be said for transaction size, the size being different based on the solution application.

For a typical blockchain solution, a fair number of transactions per day is 1000, taking into consideration that from this value on the costs are considered to be in the margins of feasibility. If there are more transactions the costs become easier to be supported. Of course, the requirements and applicability of the blockchain solution need to be evaluated also besides the details already mentioned.

B. *Proposed algorithm*

The pay-for-gain algorithm (PFG) proposed in [12] is based on game theory and loan credit theory. Its aim is to find an equilibrium condition by which to maximize the interest of each participant through cooperation. PFG is the basis of the algorithm implemented to demonstrate the feasibility of integrating a blockchain solution in an AS federation and to validate the reason for this integration. A mechanism of incentives is proposed to stimulate the cooperation of multiple AS. Therefore, individuals (AS) who do not want to cooperate and prefer an approach on their own may find that it is advantageous and optimal if they choose the option of cooperation. By implementing the mentioned algorithm, the equilibrium condition is investigated, through which the interest of each individual is maximized within the PFG scheme of the algorithm. The effectiveness of the proposed mechanism will be demonstrated and presented in the experimental section.

The integrated PFG mechanism and algorithm presented in this paper it is based on the fact that if an individual borrows something of interest (resources) from another individual several times, and the individual does not return what he borrowed, in the end the individual willing to give will not borrow any more resources or will borrow them less often. Therefore, a set of formulas is needed to consider all these aspects, as well as the aspects given by the problem in question for which it must demonstrate the feasibility and validity of the cooperation. These formulas are adapted from [11] to the take into account the cooperative context and characteristics of the technologies needed.

In the proposed algorithm a node represents an AS - the individuals between which the actions take place. In order to quantify the interaction between nodes and their contribution in the coalition for the blockchain integration, the following formulas are used (1) – (3):

$$resources\_for\_B = g(sum\_for\_B) \times resources\_for\_A \tag{1}$$

$$g(sum\_for\_B) = \begin{cases} 1, & sum\_for\_B \le initial\_resources\_amount \\ \frac{1}{sum\_for\_B}, & sum\_for\_B > initial\_resources\_amount \end{cases} \tag{2}$$

$$sum\_for\_B = \sum(resources\_for\_B - resources\_for\_A) \tag{3}$$

,where *resources_for_B* represent the resources that AS A allocates to the coalition blockchain; *sum_for_B* represents the total resources allocated by AS A to the blockchain; *resources_free_A* represents the resources that AS A has available for use in the coalition blockchain; *initial_resources_amount* represents the number of resources that an AS reserves in order to be allocated and used within the coalition blockchain; *g()* represents the function with which resources_for_B is calculated. Similarly, the formulas are used for all participating nodes.

In the algorithm, a node is defined with the following fields: an identifier (ID), the list of nodes allocated to be part of the blockchain, the resources initially set to be allocated in the blockchain (initial_resources_for_sharing), the resources available to be allocated (available_resources), the resources allocated to the blockchain in the current round (current_lent_resources) and the total number of resources that have been allocated so far to the blockchain (total_lent_resources). In each round, the node calculates its resources for blockchain allocation based on the total number of resources allocated so far.

The flow diagram in Figure 1 summarizes the algorithm's steps.

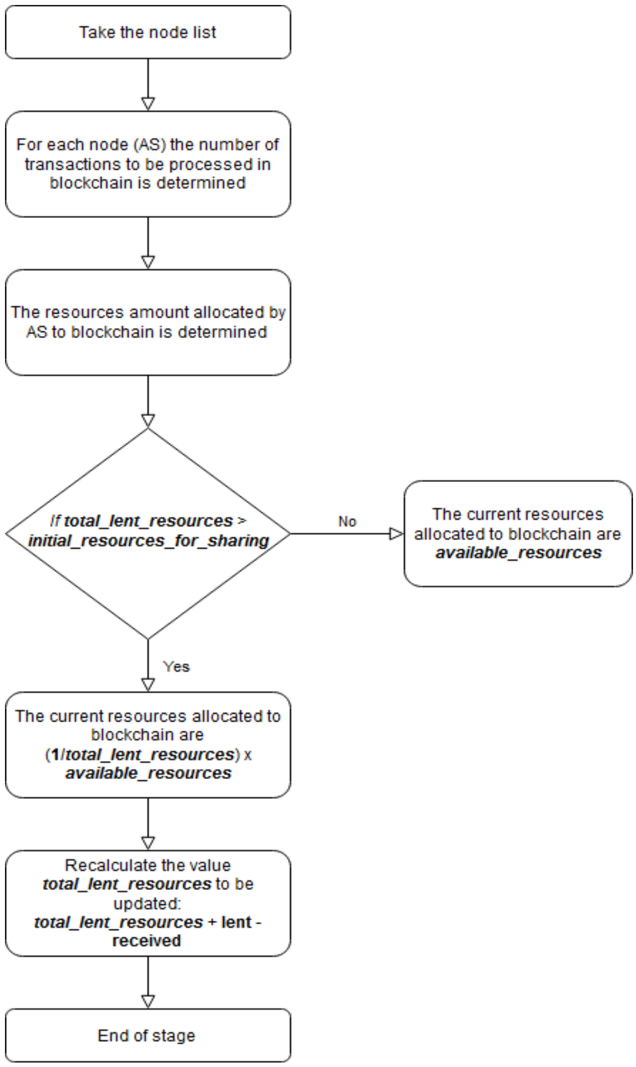

Fig. 1. Flow diagram of integrated PFG mechanism

An AS that contributes resources in the blockchain is represented as a node or individual in the presented algorithm. Each participating AS may have one or more blockchain nodes – resources/devices allocated to be part of the processing required for the blockchain. These blockchain nodes are randomly distributed to the autonomous systems in the algorithm. Each node has a maximum number of resources that can be allocated for the blockchain and an initial number (starting with) of resources that can be allocated.

The algorithm runs over a certain period of time (which can be variable) - period divided into rounds. In each round the steps of the PFG mechanism, as well as the complementary steps of the algorithm, are carried out. At the beginning of each round, an AS has a random number of transactions to process. The total value accumulated from each AS represents the transactions to be processed in the blockchain for the respective round. The processing of the mentioned transactions requires a contribution of necessary resources to cover this need. The necessary resources are calculated according to the number of transactions and their size.

There is a verification step in which the resources needed by the blockchain for a round are compared with those that were made available by the autonomous systems through their nodes. If the resources allocated by them are sufficient, then the algorithm can proceed to the next round. Otherwise, the step of allocating resources must be performed again until the condition is met, in order to be able to have the processing needed for the transactions. At the end of the round there is also a correction stage, if needed. This stage takes into account the resources allocated to the blockchain by an AS in relation to the resources used from the blockchain and regulates the amount of resources that will be available to be allocated in the next round. The purpose of this correction is to balance the number of resources that autonomous systems allocate within blockchain of the coalition / federation and to stimulate a uniform behavior regarding the allocation of resources. This verification eliminates the situations in which one AS allocates most of the resources, and the others allocate only a minimum amount required, thus taking advantage of the generous resources offered by other participants. After the elapsed time period (number of rounds) the algorithm reaches the end, and the results can be analyzed.

Following the initial simulations, a correction step was introduced which aims to maximize the benefits of participating in the coalition / federation. It has been observed that in some cases, if the number of blockchain nodes provided by each AS is more unbalanced, multi-node autonomous systems have a slower increase in coalition participation benefits than other autonomous systems. Therefore, a history has been introduced that monitors the benefit obtained by each service provider from participating in the coalition in the last three rounds. If the trend is not an ascending one and a stagnation of the benefit is noticed, with the help of the mentioned history, a recalibration of the available resources is used to be allocated in the next step. Thus, the current trend of the benefits is changed in an ascending one.

The performance constraints of blockchain, regarding the number of transactions that can be processed per day, were also analyzed. Following this analysis, a step was implemented that moves the excess of transactions for one day (round) and propagates it to be processed in the next one, in addition to the transactions associated with the respective day. This step ensures the continuity of transaction processing by eliminating the risk that they will be lost and not processed. Thus, at the end of each round the surplus transactions are buffered for the next round. In this way the processing effort becomes more balanced, avoiding significant fluctuations over time and processing rounds.

IV. SIMULATION

For simulation it is considered that the coalition integrates a private blockchain that has as a starting point 10 nodes, as per analysis discussed in [13]. These blockchain nodes are randomly distributed to the parties (ASs) involved in the algorithm. The starting number of ASs is a random between 2 and 4, having considered a distribution as balanced as possible but in the same time one that allows cases where an AS allocates a more significant number of resources than others. The amount of transactions to be processed per AS, a random value between 1000 and 2000 is considered, such a number falling in the minimum accepted values as described in [13]. Related to the simulation period, a round is considered to be the equivalent of a day. Thus, different simulation intervals can be achieved, helping for a better framing of the results over the course of time. In this way we can achieve information related to evolution in relation with time. For blockchain nodes in terms of processing resources, a value of 1 GB is considered as initial resources and a value of 4 GB is considered as maximum resources that can be allocated. These values are considered based on the resources and performance of the network devices from recent time and having an approach that takes into consideration middle tier devices (not an approach with top tier devices).

For better clarity and understanding of the results for the implemented algorithm, two more approaches were included for comparison. The standard algorithm used for comparison in game theory is tit-for-tat (TFT). This mechanism takes into account the actions of the other parties and adapts its action from the next round based on these actions. Thus, in our case if a party allocates resources for the federation's blockchain but the other does not allocate resources, the next round's action will be a punishment so no resources will be allocated. If the other participant party allocates resources then in the next round our party will allocate resources too. Because TFT mechanism does not always perform well and the results could go in a wrong way because of the punishments affecting the cooperation and the benefits, another improved mechanism was also considered. This second mechanism is called hybrid tit-for-tat (HTFT) and is different from TFT in a way that is not so strict in punishing a non-cooperative action. Thus, if a party allocates resources for the coalition's blockchain but the other party does not do this, our party has a chance (based on a probability) to forgive and not punish this behavior, so in the next round it will also allocate resources. In this way, there are more chances that this mechanism will not fall in the worst case scenario of the TFT mechanism and there are more chances for the cooperation and benefit not to be (so) affected.

Considering what was already mentioned, in the next part the simulation results are presented. As mentioned before, our simulation period for the implemented algorithms is divided into time slots. A time slot is actually a simulation round and such a round is considered to be the time spent in a day. Thus, we have a classification of three categories from this point of view in order to paint the picture as clear as possible in regard to the results obtained: behavior simulation for a short time, for a medium amount of time and for a long time. Also, we try to obtain the best projection possible of the evolution in time.

Besides the time period, the graphic shows the average value of the benefit for an AS to participate to coalition's blockchain for each round. For the short time interval simulation we considered periods of time of 1 month and 3 months. These two intervals are presented in Figure 2. In the graphics it can be observed that PFG mechanism has a sustained growth over the whole simulation period. This fact shows that the benefit of an AS is maximized by the participation to blockchain together with the other ASs. When using TFT it can be observed that the benefit is a constant value that is maintained at 0. This means that an AS will not lose benefit by participation but will not gain benefit by participating either. When using HTFT on the other hand, it can be observed that a growth in benefit is assured when ASs cooperate. This growth is comparable for short term with the one assured by PFG, as the first graphic shows, but as the time period grows the results from PFG take off having a clearer growth.

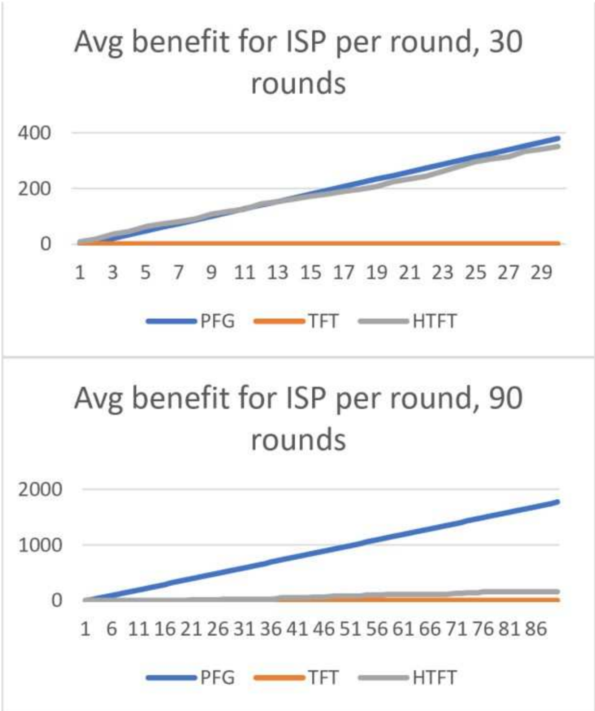

Fig. 2. PFG vs TFT vs HTFT (short term)

The second category of simulation is the one made on medium time in regard to the length of the time period. This is presented in the graphic from Figure 3.

The time periods for this category are 6 months and 1 year, respectively. When PFG mechanism is used the growth trend of maximizing benefit is maintained. It can also be observed that there is a constant growth over the whole simulation period, the benefit growing directly proportional with the simulation period. If the TFT mechanism is used, for one of the periods of time it can be observed that the same trend is maintained as for short term simulation. For the other period of time a negative case scenario is hit where the ASs lose benefit due to a faulty collaboration relation. This graphic presents the previously described case when TFT can affect collaboration in a wrong way if it goes on the wrong way with punishing actions. When HTFT mechanism is used, a growth of benefit over time is observed, but this growth is not comparable with growth provided by PFG mechanism. Besides this, the second graphic shows that even though HTFT maintains a better collaboration between the parties than the one in TFT, there are chances too that it will fall on a descending path the same as TFT does, even though these chances are more reduced.

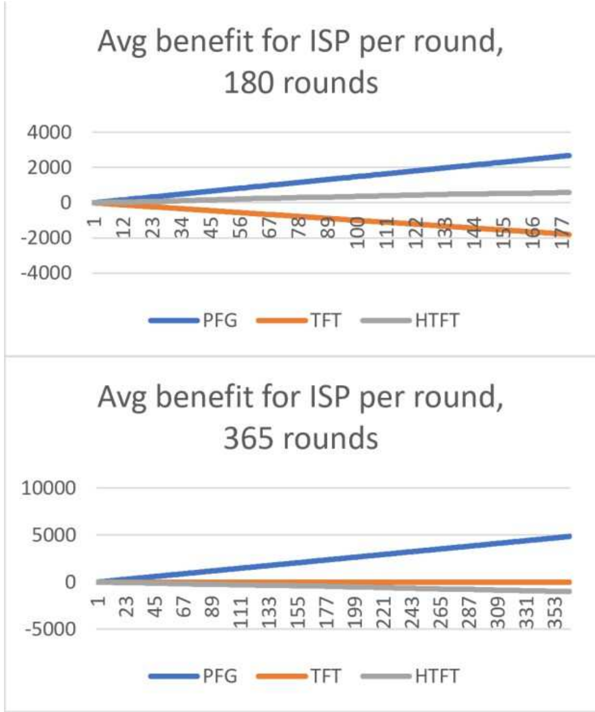

Fig. 3. PFG vs TFT vs HTFT (medium term)

Figure 4 presents the third category presented. This is the simulation over a long period of time and the time intervals considered here are 2 and 5 years respectively.

Fig. 4. PFG vs TFT vs HTFT (long term)

Because the participation of an AS to a coalition that integrates a blockchain solution is viewed as a long term action, we need to see how this would perform in terms of the long term benefits obtained. In this way we can find out if the effort of collaboration is justified and brings a positive contribution. The presented graphics help in finding the answer to this. When the algorithm that implements PFG is used it can be observed that the benefit growth maintains for long periods of time too. Another thing is that this growth is in a constant way and is a linear (stable) growth. When TFT is used it can be observed that same linear stagnation on the 0 value is maintained, but there is the case in the second graphic that shows that TFT can also take a favorable path where there is a healthy cooperation so TFT provides a growth in benefit. Anyway, the results obtained are not on the same level with those obtained by PFG. When HTFT is used it can be observed that there is a growth of benefit over time, but the growth provided here is not as big as what PFG offers.

Based on the presented graphics it can be observed that PFG assures a benefit growth that demonstrates that the collaboration done in a healthy way in integrating a blockchain benefits all parties. Besides the growth, the consistency provided in growth by the PFG mechanism can also be observed. PFG also takes into consideration that some actions could affect the growth of benefit for some participants so it limits and discourages these behaviors so the growth can be beneficial in the most favorable way to all participants. These facts cand be observed in Figure 5. This graphic compares the evolutions of PFG for every simulation period based on the average value of benefit per AS at every step. It can be observed with ease that PFG is constant and linear in growth by overlapping the simulations. This only strengthens the belief that a good and correct collaboration provides benefits over time.

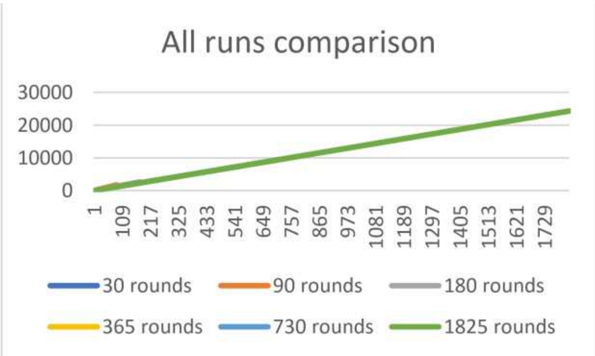

Fig. 5. Simulation comparison in regard to all time periods

V. CONCLUSIONS

The paper studies the feasibility of building a shared AS blockchain infrastructure employing a collaborative game theory approach. Using game theory, a mathematical model was used to analyze the interactions between different autonomous systems (AS) in the context of blockchain technology. The games chosen are in the category of cooperative games, where multiple actors cooperate and form a coalition which they join or leave based upon their payoffs / reward. A PFG based algorithm and its payoff function were proposed and derived from the analyzed parameters. The feasibility of integrating a blockchain solution in a federation of ASs was demonstrated.

In our simulation we have learned that if there is a discrepancy between the number of resources (blockchain nodes) allocated by the ASs for the coalition's blockchain there is also a difference in benefit growth for the ASs. In regard to the PFG approach, it was shown that there is no correlation in the number of nodes an AS provides and the increase in benefits and a maximization over time. However, there is a significant difference between the number of resources allocated by ASs, the AS that will participate with more nodes will have a slower increase in benefits than the other ASs. This happens due to the fact the amount of resources the blockchain offers for the AS with a higher allocation of resources is lower compared to the other ASs. Thus, if the amount of resources allocated for blockchain is similar for all ASs, the benefit maximization rate will also be similar. However, the actors that offer more resources are slightly disadvantaged. As a future work, a mechanism should be added to protect and promote this type of actors, so as to maximize their benefits. In this way the PFG mechanism will have stability over all areas.

The feasibility of integrating a blockchain solution in a federation of ASs was demonstrated by developing a PFG based algorithm and its associate payoff function and by comparing the proposed approach with two other games.

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