Coalitional games for energy saving in telecommunication networks

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Preface on centrality measures

In network analysis, centrality refers to measures of “importance” of vertices within a graph (e.g. aimed at identifying the most influential persons in a social network, the key proteins in a biological network, the most critical infrastructure nodes in the Internet, etc.)

Differently stated, centrality measures may help to understand at which extent the failure of a node could impact a system (network), determining the collapse or the malfunctioning of the entire system.

Basic graph theory notations

An (undirected) *graph* or *network* is a pair $\langle N, E\rangle$, where N is a finite set of *vertices* or *nodes* and E is a set of edges e of the form $\{i, j\}$ with $i, j \in N$, $i \neq j$.

A *path* between nodes i and j in a graph $\langle N, E\rangle$ is a finite sequence of different nodes $(i_0, i_1, \ldots, i_k)$, where $i = i_0$ and $j = i_k$, $k \geq 1$, such that $\{i_s, i_{s+1}\} \in E$ for each $s \in \{0, ..., k-1\}$ and such that all these edges are distinct.

For each non-empty coalition $S \subseteq N$, we call the graph $\langle S, E_S\rangle$ such that $E_S \subseteq E$ and $e \subseteq S$ for each $e \in E_S$, the *restriction of* $\langle N, E\rangle$ *to* S. If all pairs of nodes in $\langle S, E_S\rangle$ are connected, we say that coalition S is a *connected component* in E_S.

The *length* $l(i, j)$ of a path between i and j in a graph $\langle V, E\rangle$ is the number of edges in the path and a *shortest path* between i and j in a graph $\langle N, E\rangle$ is a path between i and j with minimum length, denoted by $d(i, j)$.

Centrality properties

If we have no further information about the interaction among the vertices of the graph (otehr than the graph itself) one could impose for a measure of centrality the following desiderata [8]:

$d.1$) a measure of centrality should not depend on the name of the nodes;

$d.2$) The centrality of a node in a disconnected graph should coincide with the centrality of that node in the connected component to which it belongs;

$d.3$) isolated nodes should have minimal centrality;

$d.4$) If $\langle V, E \rangle$ is a chain, centrality should increase from the end node to the median node;

$d.5$) of all connected graphs with n nodes, the minimal centrality should be attained by the end nodes in a chain;

$d.6$) of all graphs with n nodes, the maximal centrality should be attained by the hub of a star;

$d.7$) Removing an edge should decrease (or at least, not increase) the centrality of both nodes incident on that edge.

Classical centrality measures

Different measures of centrality for nodes in a network have been proposed in the literature [2, 5, 7, 10, 11]:

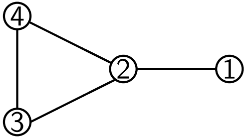
- *degree centrality* $deg(i)$ [10] of a node $i \in V$ in a graph $\langle V, E \rangle$ is defined as the number of edges in $e \in E$ such that $i \in e$.

- *betweenness centrality* [7]: let $i, j, k \in V$ and let $n_{i,j}$ be the number of shortest between i and j and let $n_{i,j}(k)$ be the number of shortest paths formed which contain node k. The *rate of communication* between i and j that can be monitored by an interior node k is denoted by $\delta_{i,j}(k) = n_{i,j}(k)/n_{i,j}$. If no shortest path between i and j exists $\delta_{i,j}(k) = 0$ by definition. The betweenness centrality of k is defined as $\sum_{i,j \in V, i \neq j, i \neq k, j \neq k} \delta_{i,j}(k)$.

- *Closeness centrality* [2] of a node $i \in V$ is defined as the inverse of the average length of the shortest paths from i to all the other nodes in the graph, that is $\frac{|V|-1}{\sum_{j \in V, j \neq i} d(i,j)}$, and it measures the extent to which node i is close to all the other nodes in the graph.

- *eigenvector centrality* [5] of node i is defined as the i-th element of the *principal* eigenvector (which is the eigenvector corresponding to the principal, i.e. largest, eigenvalue) of the adjacency matrix of the graph. This principal eigenvector is normalized such that its largest entry is 1, and it measures how a node is well connected to other highly connected nodes.

An example: the four measures of centrality introduced above



Nodes	1	2	3	4
degree	1	3	2	2
betweenness	0	2	0	0
closeness	$\frac{3}{5}$	1	$\frac{3}{4}$	$\frac{3}{4}$
eigenvector	0.46	1	0.85	0.85

- Classical centrality measures are quite appropriate to compute the importance of nodes in situations where it is justified to make the assumption that nodes failures occur independently.

- Another strong assumption that justifies the use of classical centrality measures is that the consequence of the failure of each node in the system is important (for, instance it determines the collapse of the system) and it is the same for all nodes: a situations where a system is sensible to the failure of connected components with more than one node is not considered.

- On the contrary, in many real-world networks, assuming that the actions of the agents on the nodes are independent is not realistic at all. Similarly, the consequences of an action on the system could be appreciated only if a consistent number of possibly connected agents take the same action.

Coalitional games: pros and cons

Coalitional games allow for a richer description of agents relationships in a network, where it is quite realistic to figure out the mutual influence of nodes in producing a certain outcome.

Even if coalitional games substantially contribute to a more realistic and complete description of a system, one could object that their use determines a drastic increasing of the complexity of the analysis. In fact, the evaluation of the worth of $2^{|N|} - 1$ coalitions, and their successive use for the calculations of solutions, makes the application of coalitional games very hard.

However, several studies have shown the effective possibility of applying these models to real-world networks. In these approaches, the problem of the representation of the strength of coalitions is overcome by a concise closed-form of the characteristic function and/or approximation methods for solutions.

Basic definitions on coalitional games

A *coalitional game*, also known as *characteristic-form game* or *Transferable Utility (TU) game*, is a pair (N, v), where N denotes a finite set of *players* and v is the *characteristic function*, assigning to each $S \subseteq N$, a real number $v(S) \in \mathbb{R}$, with $v(\emptyset) = 0$ by convention. If the set N of players is fixed, we identify a coalitional game (N, v) with the corresponding characteristic function v.

The Shapley value

- We define the set Σ_N of possible linear orders on the set N as the set of all bijections $\sigma : N \to N$, where $\sigma(i) = j$ means that with respect to σ, player j is in the i-th position. Let (N, v) be a coalitional game with N as the set of players.

For $\sigma \in \Sigma_N$, the *marginal vector* $m^\sigma(v)$ is defined by

$$m_i^\sigma(v) = v([i,\sigma]) - v((i,\sigma)) \text{ for all } i \in N,$$

where $[i,\sigma] = \{j \in N : \sigma^{-1}(j) \leq \sigma^{-1}(i)\}$ is the set of predecessors of i with respect to σ including i, and
$(i,\sigma) = \{j \in N : \sigma^{-1}(j) < \sigma^{-1}(i)\}$ is the set of predecessors of i with respect to σ excluding i.

The Shapley value $\phi(v)$ of a game (N, v) is then defined as the average of marginal vectors over all $|N|!$ possible orders in Σ_N

$$\phi_i(v) = \sum_{\sigma \in \Sigma_N} \frac{m_i^\sigma(v)}{|N|!} \text{ for all } i \in N. \quad (1)$$

Given a (communication) network $\langle N, E\rangle$ and a TU-game (N, v), following the approach in [9], we use the structure of an interaction network to define a new game (N, w_E^v), where the value $w_E^v(S)$ of a coalition $S \subseteq N$ equals the sum of the values assigned by v to the connected components of the network restricted to this coalition S. The game w_E^v is called the graph-restricted game. graph-restricted game (N, w_E^v). Formally,

$$w_E^v(S) = \sum_{T \in C_{E_S}} v(T) \tag{2}$$

for each $S \in 2^N \setminus \{\emptyset\}$, where $E_S = \{e \in E | e \subseteq S\}$ is the set of edges with vertices in S and C_{E_S} is the set of all the connected components in $\langle S, E_S\rangle$, and with the convention $w_E^v(\emptyset) = 0$. The Shapley value of game w_E^v is known as the *Myerson value* [9] of the *communication situation* $\langle N, v, E\rangle$ and denoted by $\mu(v, E)$.

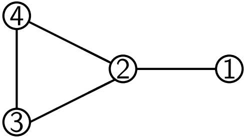
The Myerson value

Consider the Myerson value of a communication situation $\langle N, v, E\rangle$, where v is a *symmetric* game, i.e. $v(S) = f(s)$ for each $S \subseteq V$, $S \neq \emptyset$, where s is the cardinality of S, and the function $f : \{1, \ldots, |N|\} \rightarrow \mathbb{R}$ satisfies $f(0) = 0$.

Imposing v as symmetric, it can be checked that all the desiderata $d.1, \ldots, d.7$ are satisfied by the Myerson value $\mu(v, E)$. Then the Myerson value of a communication situation with symmetric game can be considered a centrality measure, but using more information then the one included in the network.

An example

Consider the meeting game defined by $v(S) = f(s) = 2^s - s - 1$, where coalition receives a unit for each possible meeting among two or more of its members, corresponding to the number of subsets of S with cardinality at least two, and the following communication network:



The meeting game with $N = \{1, 2, 3, 4\}$ is such that $v(i) = 0$, $v(i, j) = 1$, $v(i, j, k) = 4$, $v(N) = 11$.

Now, consider the graph-restricted game. Take for instance coalition $S = \{1, 3\}$: node 1 is not connected to 3 in $\langle S, E_S \rangle$; so, $w_E^v(1, 3) = v(1) + v(3) = 0$. The graph-restricted game (N, w_E^v) is such that $w_E^v(3, 4) = w_E^v(2, 4) = w_E^v(2, 3) = w_E^v(1, 2) = 1$, $w_E^v(2, 3, 4) = w_E^v(1, 2, 4) = w_E^v(1, 2, 3) = 4$, $w_E^v(1, 3, 4) = 1$, $w_E^v(1, 2, 3, 4) = 11$ and $w_E^v(S) = 0$ for all the remaining coalitions.

The Myerson value is

$$\mu(v, E) = (\tfrac{28}{12}, \tfrac{44}{12}, \tfrac{30}{12}, \tfrac{30}{12}).$$

Note that node 2 receives the highest value centrality: his contribution to form conferences is in fact the highest. Note also that nodes 3 and 4 receive the same amount of centrality, as expected, since they are symmetric in the game. In this example, the Myerson value preserves the ranking of nodes provided by the classical measures of centrality like degree, closeness and eigenvector. However, the gap between node 1 and 3, or between 1 and 4, according to the Myerson value is quite small.

Green for ICT

The carbon footprint of Information and Communication Technologies (ICT) represents today up to 10% of the global CO2 emissions, according do different estimations

Among the main ICT sectors, 37% of the total emissions are due to telecommunication infrastructures and their devices, while data centers and user devices are responsible for the remaining part

ICT itself represents a strong contribution to the environmental impact of human activities, and is growing really fast:
- Same footprint of the airplane transports, but with higher growing rate.

Green for ICT: A Hot Topic

Power consumption of networking devices scales with the installed capacity, rather than the current load.

In turn, devices are underutilized, especially during off-peak hours when traffic is low.

This represents a clear opportunity for saving energy, since many resources (i.e., routers and links) are powered on without being fully utilized, while a carefully selected subset of them can be switched off or put into sleep mode without affecting the level of Quality of Service (QoS) offered by the network.

Objectives

Adopting an energy-aware routing approach in a backbone network, keeping into account the criticality of devices in the considered network scenario.

Proposing criticality metric accounting for:
(i) the network topology, and the importance of the devices in keeping the network connectivity,
(ii) the amount of traffic that the devices are routing, and
(iii) different network configurations, corresponding to devices being turned off to save energy

Resource consolidation

The problem of resource consolidation [4] may be formalized as an optimization problem, where the objective is the minimization of the total network power consumption, and constraints include the classical connectivity constraints, and QoS constraints.

The main limitation of the resource consolidation problem is the fact that the set of devices to be switched off to save energy is chosen on the basis of the sole energy costs, and does not take into account the “importance” of devices in the network scenario.

Device ranking

Classical measure have been used in the literature for ranking network devices, looking to the network topology or to the traffic volume passing through the network element.

The most widely used topology based rankings are:
The Degree centrality is defined as the number of links connected to each node.
The Betweenness centrality represents the number of shortest paths in which a node participates.
The Closeness centrality gives the average distance between a node and all the other ones, in which the more critical nodes are the ones with the lowest closeness centrality.
Lastly, the Eigenvector centrality corresponds to the influence of a node in the network by taking into account the importance level of its neighbours.

The traffic volume based rankings solely takes into consideration the amount of traffic that is routed by the network elements.

Green Game

We model the resource consolidation problem as a cooperative Transferable Utility Game (TU-Game). This game, namely the *G-Game*, takes as its only inputs the network topology, i.e., the set of links and devices, and the traffic matrix, i.e., the amount of traffic routed by the network between each pair of devices.

The Shapley value of a G-Game defines a joint topology-aware and traffic-aware ranking of the network devices, that can profitably be used to drive the resource consolidation process.

Ingredients of a G-Game

A backbone network is represented by a graph $G = \langle N, E \rangle$, where the set of vertices or nodes N represent the interconnection nodes (routers, switches, etc.), and the set of edges E represents the set of communication links between pairs of nodes.

The load imposed to the network, seen as a whole, is defined by a traffic matrix, $T = (t_{s,d})_{s,d \in N}$, in which an element $t_{s,d}$ represents the volume of traffic entering the network through node s and exiting through node d.

The Green game

We consider a coalitional game (N, w) such that for each $S \subseteq N$, $S \neq \emptyset$ we have

$$w(S) = \sum_{i,j \in S, i \neq j} (t_{i,j} + t_{j,i}) c_{ij}(S)$$

, where

$$c_{ij}(S) = \begin{cases} 1 & \text{if } i \text{ and } j \text{ are connected in } G \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

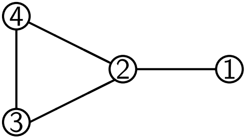
for each $S \subseteq N$, $S \neq \emptyset$

Note that the game w can be seen as the restriction to the graph G of the game (N, v) such that

$$v(S) = \sum_{i,j \in S, i \neq j} (t_{i,j} + t_{j,i}) u_{\{i,j\}}(S),$$

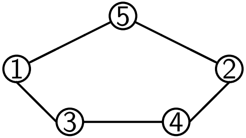
where $u_{\{i,j\}}$ is the unanimity game over $\{i, j\}$.

Example



Suppose the traffic matrix is such that $t_{1,3} = 10$ (MBps) and $t_{1,4} = 5$ (MBps) and all the other values of traffic within the matrix are null.
The G-game (N, w) is then such that $w(1, 2, 3) = 10$, $w(1, 2, 4) = 5$, $w(1, 2, 3, 4) = 15$ and $V(S) = 0$ for any other coalition of N.
The G-game is the restriction to the graph of the game $v = u_{\{1,3\}} + u_{\{1,4\}}$ that is not a symmetric game.

Another example



Suppose the traffic matrix is such that $t_{1,2} = 50$ (MBps) and all the other values of traffic within the matrix are null.

The G-game (N, w) is then such that $w = 50c_{1,2}$, that is $w(1,2,5) = w(1,2,3,4) = w(1,2,3,4,5) = 50$ and $V(S) = 0$ for any other coalition of N.

Note that $c_{1,2}$ is precisely the restriction to the graph of the unanimity game $u_{\{1,2\}}$, and can be decomposed in a sum of unanimity games

$$c_{1,2} = u_{\{1,2,5\}} + u_{\{1,3,4,5\}} - u_{\{1,2,3,4,5\}}.$$

More in general

Every game c_{ij} can be formulated using the formula

$$c_{ij} = \sum_{k=1}^{K_{ij}} \Big(\sum_{p \in \mathcal{P}_k(\mathcal{M}_G(i,j))} (-1)^{k+1} u_{\pi(p)} \Big)$$

where

- $\mathcal{M}_G(i,j)$ is the set of all acyclic paths between i and j in G, and K_{ij} is its cardinality.

- for each $k = 1, \dots, K_{ij}$, $\mathcal{P}_k(\mathcal{M}_G(i,j))$ is the set composed by all combinations of the union of k paths in $\mathcal{M}_G(i,j)$

-$u_{\pi(p)}$ is the unanimity game over the unanimity coalition composed by nodes in the union of paths p.

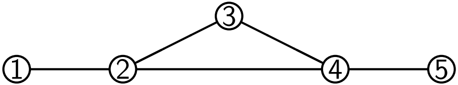
“Augmented” paths

The formula introduced in the previous slide is computationally quite expensive. First it needs the finding of all acyclic paths.

Luckily, some acyclic paths shall not be considered. Consider two paths, p and q between i and j such that all nodes in p are also in q. We say that q is an *augmented path*.

Nodes in q but not in p do not provide any alternative when a node in p is switched off. Therefore they should not increase their score for participating in path q.

Example of augmented path



here the path $(1, 2, 3, 4, 5)$ is an augmented path (w.r.t. the path $(1, 2, 4, 5)$).

In fact using the formula we have that

$$c_{1,5} = u_{\{1,2,3,4\}} + u_{\{1,2,3,4,5\}} - u_{\{1,2,3,4,5\}}$$

so the contribution of the augmented path disappears! Good news, we have a smaller subset of paths to be considered.

Finding all valid paths

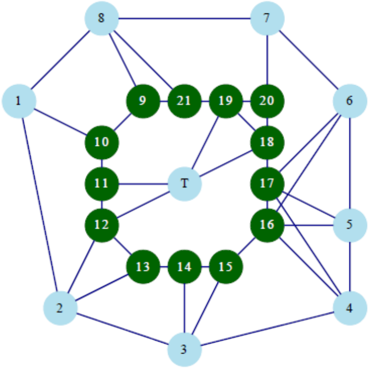
Computing the Shapley value is still computationally intensive. First, for every non-null entry in the traffic matrix, $t_{i,j}$, we need to find all valid (i.e., acyclic and non-augmented) paths from i to j.

To produce valid paths from a node i, the search visits the graph by neighbours avoiding loops and augmented paths.

First, when a branch $(i, i_1, i_2, \ldots, i_n)$ is explored, the already visited nodes $i, i_0, ..., i_{n-1}$ cannot be visited again due to the loop-less path constraint.

Second, the branch should also avoid neighbours of preceding nodes, as this would otherwise lead to augmented paths.

Example



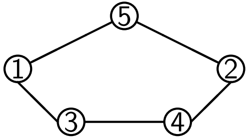
Node 9 has two neighbors: 21 and 10, but the exploration has to skip node 10, as it is already a neighbour of node 1. The exploration only needs to consider node 21, since $(1, 8, 9, 10, 11, T)$ is an augmented path with respect to $(1, 10, 11, T)$.

Shapley value of a G-game

A formula to calculate the Shapley value for the G-game:

$$\phi_l(c_{ij}) = \begin{cases} \sum_{k=1}^{K_{ij}} \left(\sum_{p \in \mathcal{P}_k(\mathcal{M}_G(i,j))} \frac{(-1)^{k+1}}{|\pi(p)|} \right) & \text{if } l \text{ belongs to } p \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

Example:



$$c_{1,2} = u_{\{1,2,5\}} + u_{\{1,2,3,4\}} - u_{\{1,2,3,4,5\}}$$

$$\phi_l(c_{1,2}) = (\frac{1}{3}, \frac{1}{3}, 0, 0, \frac{1}{3}) + (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4}, 0) - (\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5})$$

$$= (\frac{23}{60}, \frac{23}{60}, \frac{8}{60}, \frac{3}{60}, \frac{3}{60}).$$

Computational problem

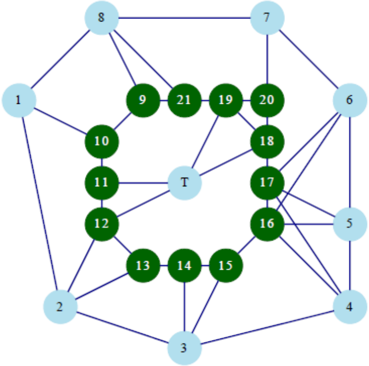
Even when only the limited set of valid paths are considered, the Shapley value computation becomes intractable as the number of paths grows: the formula requires indeed, for any non-null flow between i and j, to consider all the possible combinations of the K_{ij} paths that have been found, hence $2^{K_{ij}}$ iterations per flow.

Note that every path brings a contribution inversely proportional to its length to the Shapley value of each traversed node.

In addition, the use of very long paths (i.e., greater than the network diameter) is rare in real networks, as they would only be used in extreme cases when multiple link/node failures occur simultaneously.

Hence, bounding the maximum path length to a value L greater than the diameter would not affect the practical relevance of the solution from a networking standpoint.

A realistic scenario



we consider the reference topology of an ISP participating in the TIGER2 project (projects.celtic-initiative.org/tiger2/info.htm)

The light-shaded nodes (1 to 8) are access nodes, source and destination of traffic requests, and can not be switched off.

The dark nodes (9 to 21) are transit nodes, performing only traffic transport, and can be switched off.

Node T is the traffic collection point, providing access to the core network and the big Internet, with whom nodes typically exchange the majority of the traffic.

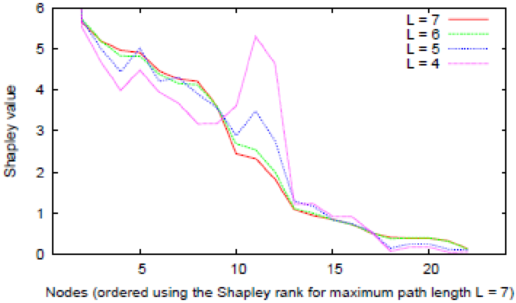


Figure 3: Node ranking for different maximum path lengths.

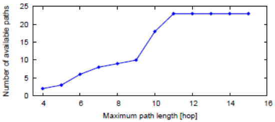


Figure 4: Number of available paths between 1 and T as a function of the maximum path length.

Reference network scenario

The power consumption Pi (in Watts) of a node, is assumed to be related to its switching capability (in Mb/s), that in turns is assumed to be twice the capacity of its entire set of connected links.

Energy saving capability is evaluated with respect to the situation in which all nodes are powered on (referred to as "Baseline" configuration).

We compute the link load by routing the traffic matrix on the resulting topology: in more detail, we use TOTEM [1] to perform an optimization of the routing weights (using the IGP-WO algorithm) and route the traffic enabling Equal Cost Multi Path (ECMP).

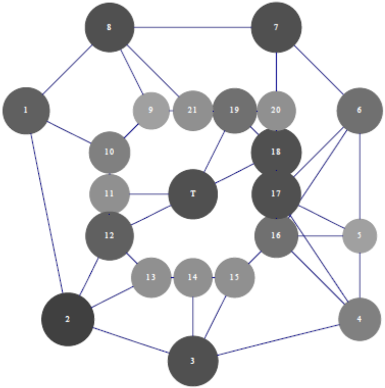
Possible rankings

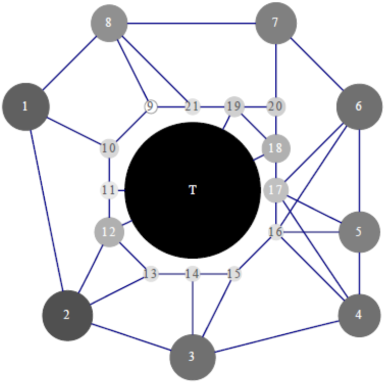
We compare all the classical centrality measures on the network topology above.

We also compare the Shapley value of two different game (max length=6 hops): (i) the G-Game with a uniform traffic matrix, referred to as G-Game U-TM hereafter, that reflects only the network topology and (ii) the full G-Game earlier defined, that considers the actual traffic matrix.

Least Flow (LF) ranking has been proposed by [6], which ranks devices on the basis of the amount of traffic they would route in the baseline configuration.

G-game U-TM vs G-game





Possible rankings

Table 1: Correlation coefficients between the rankings defined by different criteria.

	G-Game (U-TM)	Betweenness	Degree	Closeness	Eigenvector	G-Game	LF
G-Game (U-TM)	1.00						
Betweenness	0.97	1.00					
Degree	0.46	0.53	1.00				
Closeness	0.87	0.91	0.62	1.00			
Eigenvector	-0.01	0.08	0.73	0.18	1.00		
G-Game	0.41	0.43	0.25	0.51	-0.02	1.00	
LF	0.43	0.49	0.48	0.60	0.19	0.56	1.00

LF and Shapley value produce singular rankings (i.e., that are not correlated with any other).
Most topology-related rankings (Betweenness, Closeness, G-Game U-TM) are similar (very high correlation) and are evaluated only through the G-Game U-TM hereafter.
Degree and Eigenvalues also form a distinct family which is omitted below as resulting less pertinent, and performing poorly.

Energy saving vs. QoS

To evaluate the pertinence of the different rankings, we select a set of nodes that can be switched off by scanning the list sorted by increasing criticality (i.e., safest first).

The algorithm examines each node in turn, by checking whether its removal, in addition to nodes previously turned off, would prevent the network from routing the whole traffic matrix (by means of a linear program).

To evaluate the impact of this strategy on the reference network, let us fix a limit of Noff $= 3$ off nodes, so that at most 25% of the transit nodes can be switched off at the same time

Ranking	Node ID
G-Game	**9** **15** 13 14 **16** *21* 11 10 20 *19* 17 18 12 8 5 7 4 3 6 1 2 T
G-Game (U-TM)	5 **9** **14** **20** 21 15 *13* 11 10 4 16 19 6 1 12 17 8 T 7 3 18 2
LF	**9** **15** 8 7 5 4 **21** 20 2 3 1 6 14 11 10 *19* *16* 13 12 17 18 T

Underlined values identify nodes that can be switched off such that the network remains able to carry the traffic matrix. Bold values identify the first three nodes that can be switched-off.

Resulting energy saving

Table 3: Variation of the average path length (in number of hops) and achievable energy saving, considering different criticality rankings.

Ranking	Off Nodes	Avg. path length $\bar{l}$	$\bar{l}_{TM}$	Energy Saving (%)
G-Game	9, 15, 16	2.45	2.99	17.05
G-Game (U-TM)	9, 14, 20	2.92	3.40	13.43
LF	9, 15, 21	2.64	3.25	16.27
Baseline	None	2.64	3.13	0.0

Link utilization distributions

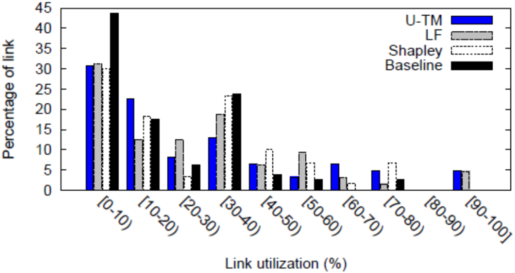


Figure 6: Distribution of the link utilization, considering different ranks and in the Baseline configuration.

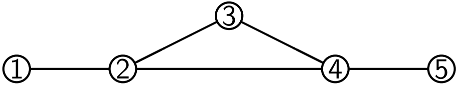
Notice that the GGame yield to excellent performances, as the link distribution is roughly equivalent to the one of the baseline configuration, where no node is switched off. Especially, maximum link utilization does not increase under G-Game (with respect the baseline configuration)

Extensions to Other Network Scenarios

we point out that different transmission technologies may require power hungry devices (e.g.,. opto/electronics signal regenerators/amplifiers) along communication links, which may move a considerable share of the energy consumption from nodes to links.

Then it may be interesting to apply a resource consolidation procedure considering network links rather than nodes.

In this new setting, players would represent links, and coalitions represent set of powered-on links, which are carrying traffic requests.



with respect to the path $(1, 2, 4, 5)$, the path $(1, 2, 3, 4, 5)$ represents an augmented path for the node-level G-Game, as it is not offering alternatives in case of node failures. When considering links as players, instead, the path $(1, 2, 3, 4, 5)$ represents a valid alternative to $(1, 2, 4, 5)$ in the case of link $\{2, 4\}$ switch-off [3].

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