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An innovative approach based on recursive clustering to design optimal districts in water distribution networks

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Abstract: Water Network Partitioning (WNP) in District Metered Areas (DMAs) is an effective management strategy for the Water Distribution Networks (WDNs), simplifying pressure control, water loss detection and protection from contamination. Nevertheless, the definition of permanent DMAs constitutes an arduous task, since, the closure of some pipes may worsen significantly the energy and the topological redundancy of the system. In recent years, several optimization procedures, relied on heuristic optimization methods, were focused on the optimal design of DMAs; they generally are based on the simultaneous insertion of gate valves in all boundary pipes defined in the clustering phase. Since these procedures are performed on the original network layout, they neglect the consequences of each pipe closure on the topology and the hydraulic performance of the network. They fail to face the optimization problem recursively since they find the optimal pipe closure at one time. This paper proposes a novel optimization procedure based on the recursive spectral clustering after each pipe closure combining, step by step, the clustering and the physical dividing phase. In this way, the optimal positioning of each next single gate valve is achieved on a novel cluster layout that takes into account the previous pipe closures. The proposed methodology is tested on a real WDN and is compared, with a non-recursive procedure, through some energy and topological performance indices.

***Keywords**:* water network partitioning; district metered areas; recursive spectral clustering

1 INTRODUCTION

WDNs can be modelled as complex networks (Boccaletti et al., 2006, Di Nardo et al., 2016a, 2018a), since they are often constituted of thousands of nodes and links, showing an irregular and strongly looped shape (as they generally developed under city streets). These topological characteristics, together with the fact that the hydraulic model equations are not linear (Mays, 2000), make WDN management arduous, with several operational problems (i.e. water and energy losses).
In the last decades, Water Network Partitioning (WNP) has become one of the most attractive and studied strategies for the improvement of WDN management; for leakage (Alonso et al., 2000) and pressure management (Water Industry Research, 1999), water quality monitoring (Di Nardo et al., 2015a), and speeding up the repairing interventions (Campbell et al., 2016). Finally, by dividing water distribution networks in District Metered Areas (DMAs), through the implementation of innovative Information and Communications Technology (ICT), remote-controlled devices and big data analysis, it is possible to change the traditional WDN management approach, transforming water networks into modern Smart Water Network (SWAN), as part of Smart Cities. The main principle is the definition of areas partially isolated from the rest of the network (permanent Districts Meter Areas (DMAs)) through the insertion of gate-valves and flow-meters along some pipes (Water Industry Research Ltd, 1999; Di Nardo et al., 2016a), implementing the paradigm of "divide and conquer" in WDN (DI Nardo et, al., 2015b).
This paradigm is part of the more general principle of the community structure, that is the process of clustering a set of elements into subgroups (or communities), such that elements in the same subgroups

have a higher similarity to each other than the elements from different subgroups (Fortunato, 2010), used for network analysis and management. Clustering analysis has been applied to many areas, from gene analysis (Huttenhower et al., 2007) to natural language processing (Ushioda and Kawasaki, 1996), from galaxy formation (White and Frenk, 1991) to image segmentation (Wu and Leahy, 1993), and transportation network (Guimerà et al., 2005). Clustering properties are exploited in order to model and predict the functioning, the behaviour and the evolution of a set of objects (or graph, i.e. structures formed by a set of *n* vertices (nodes) and a set of *m* edges (links) connecting vertices), by identifying substructures in order to improve the analysis of the system and the detection of anomalies.

In the last years, in the field of water distribution networks, several WNP procedures have been proposed in the literature for finding an optimal WNP layout (reviews are given in Perelman et al, 2015 and Di Nardo et al., 2015b); generally, they are arranged in two phases:

a) *clustering*, aimed to define the shape and the dimension of the network subgroups, balancing the number of nodes of each cluster and minimizing the number of edge-cuts (Tzatchkov et al, 2006; Herrera et al, 2010; Di Nardo et al, 2013; Alvisi and Franchini, 2014; Gomes et al, 2012; Di Nardo et al, 2018a).

b) *dividing*, aimed to the physical partitioning of the network, by selecting pipes along which flow meters or gate valves are to be inserted, minimizing the economic investment and the hydraulic performance deterioration (Ferrari et al, 2014; Di Nardo et al., 2015b). The number of possible solutions in terms of gate valves/flow meters positioning grows enormously with network size. A heuristic procedure is required in this phase (Tindell et al., 1992), because the choice of the optimal positioning of flow meters and gate valves is a NP-hard problem (Bodlaender et al., 2010).

Apart from the advantages mentioned above, WNP inevitably leads to a higher energy consumption (due to pipe closures), to an economic investment increase (due to device purchase) and to a deterioration of the hydraulic performances (due to reduction of redundancy for pipe closures) (Di Nardo et al., 2015c).

WNP constitutes a crucial management task, with the aim to balance the negative and positive aspects described above, ensuring the fulfilment of the minimum required nodal pressure and satisfying the water demand of the users. This is achieved by defining the proper number, shape and dimension of clusters, by minimizing the number of boundary pipes and then by optimally locating gate-valves and flow-meters. In this regard, since water distribution networks are constituted by thousands of elements with different hydraulic characteristics (i.e. diameter, roughness, length, etc.) and with a high spatial-temporal variability of the water flow and pressure head, big data analysis can support and improve the partitioning strategy providing specific information of the water system. Specifically, heuristic optimization procedures, for both clustering and dividing phases, can be enhanced analyzing several dynamic scenarios (changing the status of gate-valves, as reported in Cavallo et al., 2017). Therefore, the development of innovative techniques for WNP design, easy to apply in data-driven approaches and in complex demand model (with changing demand magnitude, peaks, spatial-temporal pattern), represents a challenge for scientific community (Di Nardo et al., 2018b).

Generally, WNP methodologies are based on the simultaneous insertion of gate valves and flow meters on all boundary pipes defined in the previous clustering phase. In this way, these procedures disregard the consequences of each single pipe closure on the topology and on the hydraulic performances of the network, that inevitably change. They fail to face the optimization problem recursively since they find the optimal pipe closure at one time. In fact, each pipe closure changes the network topology generating another layout, and as consequence, it affects the definition of the subsequent clusters. Evidently, a methodology based on an explicit recursive approach can also face better the design of WNP in the era of big data.

Starting from previous work of the authors (Di Nardo et al., 2016), in this paper a novel procedure, based on recursive partitioning of the network (combining step by step the clustering and the dividing phase) is proposed. The recursive approach allows to find the optimal positioning of each gate valve on a novel cluster layout that takes into account the previous pipe closures. It lays the foundation for a dynamic approach to the water network partitioning strategy.

The novelty of the present work is that the clustering phase is carried out exploiting the properties of the spectral clustering algorithm (Shi and Malik, 2000; Von Luxburg, 2007), since it performs well, it is based on a fast and analytical procedure, and gives mathematical elegance to the methodology. Another novel aspect regarding the dividing phase, both for the recursive and non-recursive procedure, consist in not using a heuristic algorithm, but a simple deterministic criterion (by sorting the boundary set pipes according to their hydraulic/geometric characteristics). The aim is to provide a simple tool that can define a sub-optimal solution to the water network partitioning task when information are not available. For this purpose, in this paper the network graph was considered un-weighted, simulating the frequent case in which many information about the system are not accessible. The proposed methodology is tested on a real WDN serving the city of Parete (close to Naples), and validated with energy and topological performance indices.

2 METHODOLOGY

As described above, generally the partitioning of WDNs is carried out according to two subsequent separate phases, the clustering and the dividing. In this way, the optimal clustering layout became the starting point for the physical dividing of the system through the definition of the optimal location of the hydraulic devices. In this paper, the two procedures are integrated, providing the optimal cluster layout and the device locations simultaneously.
As known, considering a simple graph $G = (V, E)$, where V is the set of n vertices v_i (or nodes) and E is the set of m edges e l_i (or links), a k-way graph clustering problem consists in partitioning V vertices of G into k subsets, $P_1, P_2, \ldots, P_k$ such that:

- $U_1^k P_k = V$ (the union of all clusters P_k must contain all the vertices v_i),
- $P_k \cap P_t = \emptyset$ (each vertex can belong to only one cluster P_i),
- $\emptyset < P_k < V$ (at least one vertex must belong to a cluster and no cluster can contain all vertices).

The adjacency *nxn* matrix A expresses the connectivity of the graph, where elements $a_{ij} = a_{ji} = 1$ indicate that there is a link between nodes i and j and $a_{ij} = a_{ji} = 0$ otherwise. The degree of a node is defined as the number of its connection k_i; the diagonal matrix D_k contains the degree of all nodes. From these two previous matrices, it is possible to define the laplacian matrix L, as the difference between the degree and the adjacency matrix:

$$L = D_k - A \tag{1}$$

It is demonstrated that, the normalized version of the laplacian matrix, the so called random walk laplacian matrix L_{rw}, solves the relaxed versions of the *NCut* problem (minimize the number of *cuts* – edges connecting clusters – ensure simultaneously that the clusters have balanced the size in terms of number of nodes, (Shi and Malik, 2000)):

$$L_{rw} = D_k^{-1} L \tag{2}$$

The normalized spectral clustering exploits the properties of the eigenvalues of normalized laplacian graph to define the optimal cluster layout of a network (Di Nardo et al., 2018). The definition of the optimal number of clusters is defined through the analysis of the spectrum of the laplacian matrix; in particular, with the eigangap $\Delta^L(s)$ (Von Luxburg, 2007), which corresponds to the difference between the $(s + 1)^{th}$ eigenvalue and the s^{th} eigenvalue of the Laplacian matrix, if s is the number of clusters in which the network is intrinsically shaped. According to the eigengap heuristic, the proper number of clusters s, from a topological point of view, is defined such that all eigenvalues $\lambda_1, \ldots, \lambda_s$ are small, but λ_{s+1} is relatively large. It is worth to highlight that, the more pronounced is the clustered structure of the network, the better the eigengap works. More details are provided in Di Nardo et al. (2018).
If d is the diameter and l is the length of the *i-th* pipe, the resistance coefficient l/d^5 is defined for each pipe of the water network. This coefficient takes into account the physic of the problem since the head losses are proportional to it. Regarding the pipe roughness, it is considered equal for each pipe.
The novel procedure for water network partitioning is based on a recursive spectral clustering that can be arranged in the following steps of the proposed algorithm:

1) abstraction of the water supply network as a graph $G = (V, E)$;
2) definition of adjacency and laplacian and normalized laplacian matrix;
3) computation of the spectrum of normalized laplacian matrix;
4) definition of the optimal number of clusters, s_{opt}, according to the eigengap;
5) computation of the first s_{opt} eigenvectors of normalized laplacian matrix;
6) definition of the matrix $U_{nxs,opt}$ containing the first s eigenvectors as columns;
7) clustering the nodes of the network into clusters $C_1, \ldots, C_s$ using the k-means algorithm applied to the rows of the $U_{nxs,opt}$ matrix;
8) check of the continuity of the obtained clusters C_s;
9) definition of the set of edge-cuts (or boundary pipes) N_{ec};
10) check of the constraint (i.e. number of flow meters or minimum service level, etc.); if it is satisfied go to step 11) otherwise end;
11) ranking the boundary pipes according to their resistance coefficient l/d^5;
12) close the pipe with the highest resistance coefficient;

13) go to step 3, starting from the novel adjacency matrix considering the previous pipe closure (step 12);

Step 11) and 12) constitute the novel way to carry out the dividing phase; the boundary pipes are sorted according to their resistance coefficient and then the most resistive is closed. Applying the recursive procedure for the dividing phase, the closure of a boundary pipe (according to its resistance coefficient l/d^5) ensures, from a hydraulic point of view, that the pipe is less important (it is reasonable to image that, higher resistance coefficients are typical of pipes less important from water communication point of view, i.e. with smaller diameters). Steps from 1) to 12) represent the non-recursive water network partitioning (*nR-WNP*), for which the partitioning procedure are carried out one time, and the novel dividing approach is applied just on the first clustering layout obtained for the original network, simultaneously on all boundary pipes. Step 13) constitutes the core of the proposed recursive water network partitioning (*R-WNP*) based on the closure of one pipe at each step (this closure corresponds to set the link in the adjacency matrix *as* $a_{ij} = a_{ji} = 0$). In this way, it is possible to change recursively the topology of the water distribution network and to take into account the topological perturbation due to a single pipe closure allowing to optimize the definition of permanent District Metered Areas obtained with the insertion of flow meters and gate valves.

3 CASE STUDY

The proposed methodology was tested on the WDN of Parete, a small town located in a densely populated area to the south of Caserta (Italy), with population of 11,150 inhabitants. The network has 182 demand nodes (with ground elevations ranging from 53 m a.s.l. to 79 m a.s.l.), 282 pipes and 2 sources with fixed head of 110 m a.s.l. The pressure head was assumed for all the demand nodes equal to h_{des}=25 m, while a minimum service level of h_{min}^*=19 m was fixed (sum of the height of the average building in the town -9 m in Parete- and 10 m, as prescribed by the Italian guidelines). For the hydraulic simulation (carried out in demand driven with EPANET), it was considered the day of maximum consumption in the year, for which the total demand from the nodes ranges from 7.6 L/s at night time to 77.2 L/s in the midday peak, with an average value of 36.3 L/s. Finally, the original un-partitioned water network (*OWN*) shows a low value of resilience index (Todini, 2000) and network resilience (Prasad and Park, 2004), as discussed in the following.

4 RESULTS AND DISCUSSION

According to the eigengap, the proper number of clusters, from a topological point of view, is defined in s_{opt} = 4, as shown in Figure 1, because for s=4 the difference between λ_5-λ_4 is maximum.

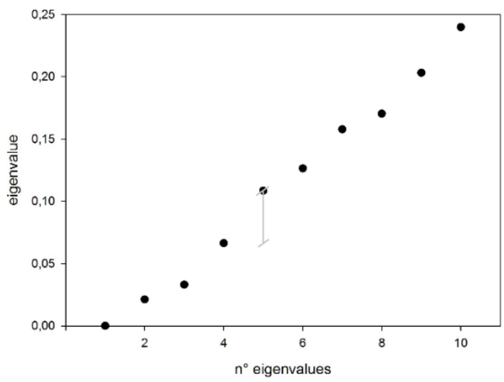

Figure 1. First ten eigenvalues of graph laplacian matrix of Parete

In order to validate the eigengap procedure, for the present case study, a topological clustering quality metric, the silhouette (Rousseeuw, 1987), was used. In particular, silhouette quantifies the consistency within clusters of data, providing a numerical value (and an easy graphical representation) of how well each network node (or element) lies within its cluster compared to other clusters. Silhouette ranges between −1 to +1, where higher values indicate that the nodes are well matched to its own cluster:

$$s(i) = \frac{b(i)-a(i)}{\max(a(i),\ b(i))} \tag{3}$$

where for each node i, $a(i)$ is the average distance between i and all other elements within the same cluster (the smaller the value, the better the assignment of the element to the cluster); and *b(i)* is the lowest average distance of *i* to all the other elements in any other cluster. In other terms, a value of *s(i)* close to 1 means that the elements are appropriately clustered. The average of all values of *s(i)* of network nodes – indicated as S_{mean} – quantifies of how appropriately all the elements have been clustered.

In Figure 2, the silhouette for the clustered nodes of the graph of Parete is shown; it is clear that most of them show a value *s(i)* > 0.7 with a S_{mean} = 0.73, which indicates the good quality – from a topological and connectivity point of view – of the clustering.

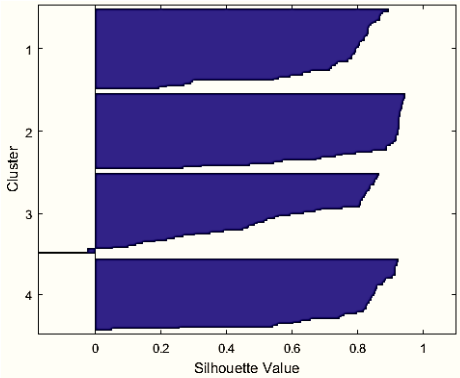

Figure 2. Silhouette diagram for the four defined clusters for the WDN of Parete

The partitioning layout with four DMAs, obtained with the *nR-WNP* and with the *R-WNP* respectively, are reported in Figure 3a and 3b, highlighting with different colors the nodes belong to DMA1, DMA2, DMA3, DMA4. It is clear that the two partitioning layout are very similar, in terms of nodes and shapes. Anyway, also small difference in boundary pipe locations can change significantly the hydraulic and topological performance of the water distribution network, as pointed out in the following by the simulation results. This aspect, confirm the necessary of carry out a recursive partitioning of the system, that takes into account at each step topological and hydraulic changes.

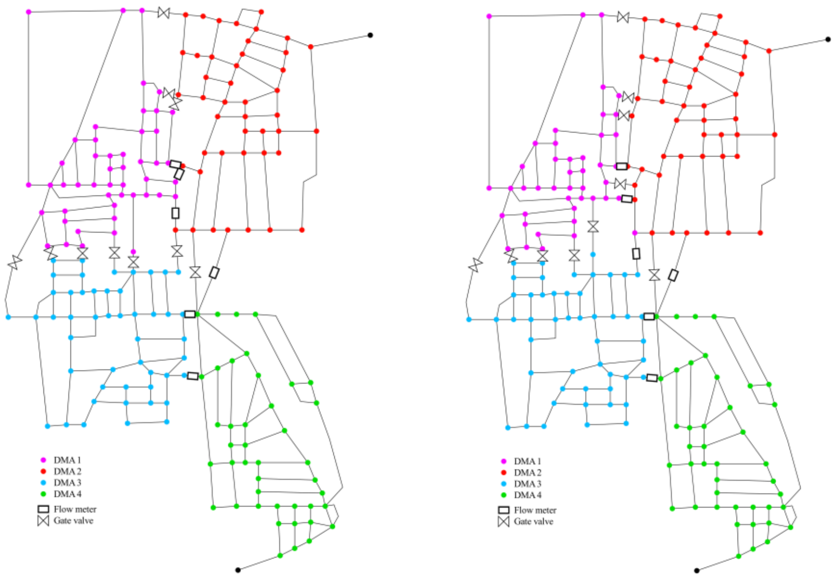

Figure 3. Comparison between a) *nR-WNP* and b) *R-WNP* layouts

In the present work, the constrain was established for the number of flow meters, which was fixed equal to N_{fm}=6, in order to simplify the water balance for each DMA (less the number of flow meters simpler is water balance computation for each DMA).

As first consideration, for the *R-WNP* procedure, the sum of the resistance coefficient l/d^5 for all the closed pipes is R_{tot}=844 m^{-4}, while for the *nR-WNP* procedure R_{tot}=491 m^{-4}. It is evident that, recursive procedure provides the closure of the most resistive pipes and leaves open the most conductive, that

could lead to a less perturbation of the system.
In order to compare the recursive and non-recursive methodology, some hydraulic and topological performance indices was computed and reported in Table 1 also with reference to un-partitioned original water network (*OWN*).
The number of edge-cuts is N_{ec}=16 for both the procedures (a small percentage of the total number of pipes, around 5.6%, ensuring a less hydraulic deterioration in the subsequent dividing phase).
Another quality metric for the clustering is the balance index I_b, defined as the standard deviation of the number of nodes for each cluster. It is clear that, the two clustering layout are quite balanced in terms of elements, with a small value for the balanced index, equal to I_b=2.45 (with n_1=48, n_2=45, n_3=48, and n_4=43) for the *nR-WNP* and I_b=3.36 (n_1=43, n_2=49, n_3=49, and n_4=43) for *R-WNP*. It means that, the *nR-WNP* provides a clustering layout slightly more balanced than *R-WNP*.

Table 1. Hydraulic and topological metrics for the original network (O*WN*), partitioned network with non-recursive procedure (*nR-WNP*), and partitioned network with recursive procedure (*R-WNP*)

Index	OWN	nR-WNP	R-WNP
N_{ec}	-	16	16
I_b	-	2.45	3.46
D	20	27	23
APL	8.80	10.84	10.46
λ2	0.021	0.006	0.009
h_{min}	21.36	16.36	19.63
h_{mean}	31.05	28.76	29.44
h_{max}	50.47	49.91	50.16
I_r	0.35	0.21	0.26
N_r	0.32	0.19	0.24

From a topological point of view, the solution provided by the recursive procedure show better values of the communication and robustness metrics (Giudicianni et al., 2018). In particular, the Diameter *D* of the network (the largest of the shortest distance between any pair of vertices) is significantly higher for the *nR-WNP* than *R-WNP*, respectively *D*=27 and *D*=23. The average path length *APL* (the average number of steps along the shortest paths for all possible pairs of nodes in the network), even if with a small difference, is lower for the *R-WNP*. Both metrics confirm that, from a communication point of view (Watts, 1999), the layout provided by the *R-WNP* is better than that obtained with the *nR-WNP*.
Another important topological metric computed is the algebraic connectivity $\lambda 2$, which corresponds to the second smallest eigenvalue of the laplacian matrix *L* of the network graph. It is important to highlight that the spectrum of the laplacian matrix provides important features about the structure and the functioning of a network (Fiedler, 1973). In this regard, the algebraic connectivity quantifies the strength of network connections even if the graph is sparse ("how strong" are network connections). Its properties are strongly related to the analysis of graph robustness in terms of node and link failures, and proneness to clustering (i.e. the larger the algebraic connectivity is, the more difficult it is to split the network into independent components). Regarding the case study, it is clear that, both the solutions deteriorate topological robustness of the network but, as shown in Table 1, also for the algebraic connectivity, the optimal layout is provided by the recursive procedure, with $\lambda 2$=0.009 against the $\lambda 2$=0.006 of the non-recursive method.
From a hydraulic point of view, it is worth to highlight that the un-partitioned WDN of Parete has a minimum head pressure h_{min}=21.36 m lower than the design pressure h_{des}=25 m. Consequently, the permanent partitioning of the system in DMAs becomes even more an arduous management task, since the original water network shows a low value of energy resilience (Todini, 2000) I_r=0.35 and of network resilience (Prasad and Park, 2004) N_r=0.32. The aim is to carry out the partitioning of the system minimizing the pressure head deterioration (as described above, it was fixed h_{min}^*=19 m).
The most important difference between the two procedures is that, as reported in Table 1, the recursive procedure *R-WNP* satisfies the constrain of the minimum service level, with h_{min}=19.63 m, while the non-recursive procedure *nR-WNP* shows a significantly lower value, with h_{min}=16.36 m. The less deterioration of the hydraulic performances obtained with *R-WNP* with respect to *nR-WNP* are also confirmed by the mean and maximum head pressure, equal respectively to h_{mean}=29.44 m and h_{max}=50.16 m (for *R-WNP*) and h_{mean}=28.76 m and h_{max}=49.91 m (for *nR-WNP*).
Also regarding global resilience metrics, non-recursive procedure *nR-WNP* provides a higher general deterioration of the water distribution network, with a I_r=0.21 and N_r=0.19, while recursive procedure *R-*

WNP shows better values, respectively I_r=0.26 and N_r=0.24.
All simulation results confirm the effectiveness of the novel recursive methodology; indeed, DMA layout shows better hydraulic and topological performances.

5 CONCLUSION

The proposed methodology, based on the implementation of a recursive procedure, allows to define a water network partitioning significantly better, in terms of hydraulic and topological performance, than the WNP obtained with a non-recursive procedure. The novel approach is based on the idea that, in water distribution networks, after each pipe closure, the topology and the hydraulic performance of the network inevitably change. This is an aspect that is generally neglected.
The novel approach exploits the properties of the spectral clustering algorithm to better manage the recursive actions; the optimal positioning of each subsequent gate valve is achieved on a novel cluster layout that takes into account the previous pipe closures. Further, also the dividing phase is carried out in a simplified not heuristic way, closing at each step the pipe with the highest resistance coefficient l/d^5, which are reasonably those that deteriorate the network less from a hydraulic point of view.
The results show the effectiveness of the procedure from both hydraulic and topological point of view, providing a partitioning layout more resilient and robust. The procedure is fast and easy to apply and it can be tested also in dynamic operational scenarios driven by big data availability.
The procedure could be further improved weighting the graph of the network with geometric characteristics of pipes (i.e. diameter, length, resistance, conductivity, etc.), or using the output of the hydraulic simulation (i.e. water flow, velocity, dissipated power, etc.), or fixing other hydraulic constraints. In this regard, the availability of a huge amount of information about water distribution network could provide the real behavior of the system after each step. Another aspect to highlight is that the dividing phase can be carried out also through an optimization algorithm that provides the minimization of multi-objective functions (i.e. the hydraulic deterioration of the system after each pipe closure). Further works will test the several possible combinations of weights/constraints/objective functions, in order to provide a general optimal iterative procedure for the water network partitioning.

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