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# A proposal of optimal sampling design using infrastructure modularity

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**Abstract**

Planning of pressure observations/meters in terms of spatial distribution and number is named sampling design. In the past, the hydraulic model calibration was the main driver of the sampling design. Today, water utilities are interested in system pressure monitoring for hydraulic system analysis and management with respect to other technical purposes as for example detection of anomalies (burst leakages and anomaly head losses) and service quality with respect to customers. In recent years, the optimal location of flow observations/meters, related to design of optimal district metering areas, has been faced considering optimal network segmentation and the modularity index using a multi-objective strategy. The original modularity index from the studies of the complex network theory was transformed to be WDN-oriented. Consistently, this paper proposes a new way to perform the sampling design using newly developed sampling-oriented modularity-based metrics. The strategy optimizes the location of the pressure meters based on network topology creating pressure district metering areas, i.e. it returns the optimal location of the nodal pressure meters defining “pressure DMAs”. The multi-objective optimization problem minimizes the cost of newly installed meters while maximizing the sampling-oriented modularity metrics. The battle of background leakages assessment water network (BBLAWN) allows presenting and discussing the proposed sampling design methodology.


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*Keywords:* Water distribution network; Sampling design; Modularity index; Segmentation; Multi-objective optimization

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## 1. Introduction

The analysis and management of large water distribution networks (WDNs) has always presented many problems related with non-homogeneous behavior and the growing amount of field information (i.e. streams of data), that are available nowadays by ICT solutions, are increasing the complexity of WDNs analysis. Over time, several solutions have been proposed to manage this problem, and the most commonly used and studied is the community detection, i.e. the division of the network into smaller modules segmenting the hydraulic system [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11].

The community detection strategy [12] [13] allows the WDNs (infrastructure networks) division into modules (also named segmentation or partitioning) defining a number of smaller portions (named districts, segments or modules) bounded by installed devices, suited for different technical purposes including monitoring of background leakages, detection of anomalies (e.g. due to pipe bursts), etc. [14].

In complex network theory, several metrics have been proposed for network segmentation each of them showing various advantages and drawbacks. The modularity index [13] [15] is the most widely accepted and used metric to measure the propensity of the network division into modules (actually named communities, consistently with the earliest applications of the index). The modularity is a descriptive measure of topology and relies strictly on the network structure. The advantage of the modularity is the fact that it can be computed using only the adjacency matrix of the network, without requiring other information. For a given network, a higher value of the maximum modularity index indicates a better identification of communities; therefore, the maximum value of the modularity corresponds to the maximum degree of segmentation.

Several researchers [9] [10] used the maximization of modularity index for segmentation of WDNs, i.e., infrastructure networks, although its original formulation [16] was proposed for immaterial networks. For this reason, Giustolisi and Ridolfi [17] tailored the original modularity index in order to obtain a WDN-oriented modularity index.

They considered the "conceptual cuts" segmenting the network close to nodes instead of the middle of pipes, introducing the pipe weights and defining a different modularity index aimed at dividing the network in modules having an internal similarity of an assumed pipe attribute. For instance, a modified modularity index allows the division into modules having internal similar attribute such as diameters or elevations, as opposite to the original formulation dividing the network in modules, which are similar to each other with respect to a specific weight. Afterwards, Giustolisi and Ridolfi [18] proposed the infrastructure modularity index to overcome the resolution limit of both original [19] and WDN-oriented modularity.

The segmentation problem [17] [18] was solved using a specific multi-objective evolutionary optimization strategy, based on the use of genetic algorithms (MOGA). The approach proved to be effective because WDNs are not large size networks (if compared with other typical immaterial complex networks) and the division into modules needs to be performed just few times in WDN service life. In addition, the MOGA strategy allows searching for the optimal trade-off between the minimization of the segmentation cost versus its effectiveness (i.e., the maximization of value of the WDN-oriented or infrastructure modularity indexes), which is the Pareto front of solutions.

Starting from the work on segmentation of Giustolisi and Ridolfi [17] a novel sampling-oriented modularity indices and a MOGA optimal sampling design is here proposed. The original WDN-oriented modularity [17] is modified to consider the positioning of nodal pressure meters as "conceptual removal of nodes" instead of "conceptual cuts" of the original segmentation procedure. Consequently, the optimization strategy finds the best trade-offs between sampling-oriented modularity index and cost of the newly installed devices, minimizing the number of conceptual removal nodes (i.e. pressure meters) while maximizing the sampling-oriented modularity metric. This strategy aims at providing conceptual scenarios of network division, which are the basis for the design of actual pressure metering areas. In the case of the segmentation by nodal removal, the nodes that are conceptually removed are the candidate position for pressure meters.

The originality of such approach relates to the fact that the "conceptual removal of nodes" divides the networks into "pressure DMAs". This way, each "pressure DMA" results bounded by a sub-set of nodal pressure meters, which guarantees the information about pressure status at the boundary of each pressure district of the network. In other words, "pressure DMAs" are connected each other by nodes where pressure devices are installed, which are the boundary conditions for internal pressures, similarly to flow measurements of classic DMAs for all demand