Traffic Matrix Estimation Enhanced by SDNs Nodes in Real Network Topology

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***Abstract*—Traffic matrix estimation in communication networks is challenging problem, whose solution provides a valuable management and planning tool. Given the range of technologies able to reconfigure the resource assignment, real-time knowledge of the traffic matrix enables smart adaptive traffic management functions. A new perspective is given to the traffic matrix estimation problem by the Software Defined Network (SDN) concept. We investigate an evolutionary approach, where SDN nodes are introduced into a traditional IP network, to understand how their new capabilities affect the statement and accuracy of the traffic matrix estimation problem. By referring to operational networks and benchmark measured data, we show that a major boost of estimate accuracy can be obtained with very few SDN nodes, performing very simple tasks. To that end we develop an underlying theory that helps locating SDN functionalities in the most convenient way.**

***Index Terms*—Traffic Matrix, Software-defined network.**

I. Introduction

Traffic matrix estimation consists of assessing the amount of data transferred between a source node and a destination node of a network for all couples of nodes. Equivalently, ingress and egress links, connecting the target network to the users, can be considered as "source node" and "destination node", respectively. As a matter of example, the target network can be the Internet Service Provider (ISP) infrastructure, a given Autonomous System in the Internet, or the core network of a cellular communications operator.

The knowledge of the traffic matrix is an extremely useful tool to monitor the network usage and load trends, to provide input for provisioning and planning functions. If estimation can be carried out on a tight time scale, e.g., every few minutes, it is conceivable to use the estimated traffic matrix values to drive adaptive resource assignments to logical paths inside the observed network so as to meet the time varying demand, given the available resources of the physical transport network. A number of technologies allow assignment of capacity to logical paths, e.g., MPLS [1], SDH LCAS [2], optical networks where light paths are designed according to a routing and wavelength assignment problem [3]. Also routing could be adaptively optimized given a sufficiently accurate knowledge of traffic matrices. A specialised important application of traffic matrix estimates is in data center networking [4], where balanced and efficient usage of processing and communication capacities is critical.

The traffic matrix estimation problem has been investigated for quite some time. The early contribution [5] is based on entropy maximization principle applied to the transportation context. The problem of origin-destination (OD) vehicular flow estimation has many similarities with the analogous issue in the communication networking environment. Tomogravity model [6] is a well known approach, conjugating gravity laws and least square methods to solve the under-determined linear system that ties the origin-destination traffic flow intensities and the network link loads. Eum et alii [7] demonstrate that the accuracy of the Tomogravity and EM methods depends strongly upon the underlying assumptions of these models, as well as the selection of an appropriate prior traffic matrix. In [8] long-range dependence of Internet traffic is exploited to define an alternative estimation process for the traffic matrix that Authors claim to be more robust than traditional methods. A weak point of that approach is that it assumes specific properties of the underlying traffic process. A sophisticated approach based on Kalman filters is adopted in [9]: this allows tracking the traffic matrix evolution with time. A drawback of this approach is the need to fit the Kalman filter parameters based on known traffic matrix samples. An extensive, solid contribution based on an information theoretic approach is offered in [10]. Casas et alii [11] address on-line traffic matrix estimation. An experimental investigation of traffic matrix estimation is given in [12]. Takeda and Shiomoto [13] propose large-scale traffic matrix estimation methods using a divide-and-conquer approach. The network is divided into multiple blocks, traffic matrices are estimated per block and estimation results are combined. Hohn and Veitch [14] investigate how to infer information on traffic flows from sampled packet level measurements.

The above picture can be read in a new light under the advent of the Software Defined Network (SDN) paradigm [15][16]. In SDN the network control is decoupled from forwarding devices. The forwarding devices (network switches) contain one or more flow tables each of which determines how packets belonging to a flow will be processed and forwarded. Flow entries typically consist of match fields, actions and counters. The last ones are used to collect statistics for a particular flow, such as number of received packets, number of bytes and duration of the flow. These specific capabilities of the SDN network switches make them useful statistic gathering points able to enrich the knowledge about the traffic flowing in the network, so they can provide additional information in the traffic matrix estimate process. Specifically, we consider an hybrid IP/SDN network composed of IP routers and SDN

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switches. The traffic metering functionality of the latter ones is used to improve the traffic matrix estimation.

We build upon the several proposed estimation methods, i.e., our approach can exploit any of those methods. Our major contribution lies in the following points: i) an in-depth investigation of the structure of the under-determined linear system that ties origin-destination traffic flows intensities and network link loads, so as to quantify the accuracy gain offered by adding more information; ii) identification of the role of SDN nodes under different insertion and usage scenarios, to acquire new "equation" of the linear system that yields the traffic matrix entries.

In Section II we connect the SDN deployment scenario with the traffic matrix estimation issue. Section III introduces notation and sets up the estimation problem by means of a mathematical formal statement. Numerical results are illustrated in Section IV and conclusions are drawn in Section V.

II. The hybrid IP/SDN network scenario

The availability of high throughput SDN switches will lead in the near future to a rapid evolution of Internet Service Provider (ISP) networks. The evolutionary strategy towards the deployment of a full SDN network requires short-medium term steps, where legacy devices (i.e. IP routers) and SDN switches have to coexist [16]. We refer to such network scenario as hybrid IP/SDN network. The management and operation of hybrid networks is attracting the attention of the research community since it requires the introduction of new functionalities allowing the communication among legacy and SDN devices: from the definition of new network models [16], to the implementation of specific management solutions [17] and new traffic engineering algorithms [15], [18].

An hybrid IP/SDN network is composed of IP routers and SDN switches. Legacy IP routers perform packet switching on the basis of the IP routing table, using the IP destination address of incoming packets for the selection of the outgoing port. The SDN switches have a more sophisticated forwarding table, able to perform packet switching on the basis of different packet fields: Layer2 source and destination addresses, IP source and destination addresses, source and destination ports, and much more [19]. A further feature of SDN switches is that for each table entry they provide a field dedicated to traffic counter: in other words an SDN switch stores the number of packets (bytes) that matches a specific entry. In this work we exploit this functionality of SDN switches to improve the traffic matrix estimation, as better explained in the following.

An hybrid IP/SDN network provides a greater flexibility, with respect to a legacy network, in terms of paths availability thanks to the programmability of SDN forwarding table: entries are not computed by a distributed routing protocol (such as OSPF) that executes a paths computation algorithm, but can be directly inserted by a centralized controller. Then, we define two different SDN operation modes:

- an IP-like behavior, where the forwarding matching can be performed only on destination IP addresses;
- a full-SDN behavior, where the forwarding matching can be performed on all fields supported by the SDN switches.

We focus on SDN switches with IP-like behavior; this operation mode makes an SDN switch very similar to an IP router, in terms of forwarding capabilities. We believe that this operation mode represents the short-term step for the introduction of SDN switches in ISP networks since network operators can still use their current operation and management protocols, introducing an SDN controller that allows to manage the SDN switches and takes care of the communication among them and IP legacy devices. We focus on the IP-like behavior since the higher granularity of forwarding actions provided by the full-SDN behavior is not very significant for ISP networks, where aggregated traffic is carried.

The only difference among an SDN switch with an IP-like behavior and an IP router is represented by the availability of a counter field in each entry of the forwarding table. Considering that an entry of an SDN switch with IP-like behavior identifies a specific destination network, the counter field represents the amount of traffic directed to such destination through the SDN node. The idea of our work is to evaluate if this information can be exploited to improve the traffic matrix estimation procedure and if it is possible to define a placement strategy of SDN nodes able to maximize the improvement.

In the next section we formulate a theorem related to the traffic estimation problem in an hybrid IP/SDN network with IP-like SDN nodes.

III. Problem Statement

Let us consider a network composed of the set $\mathcal{N} = \{n_i\}_{i=1,\dots,N}$ of N distinct nodes and the set $\mathcal{L} = \{l_i\}_{i=1,\dots,L}$ of L directional links with single and shortest path routing. Let $R \cdot X = Y$ be the system of linear equations representing the constraint for the problem of traffic matrix estimation, where Y represents the link load vector (sometimes referred to as link count vector), X the origin-destination (OD) traffic organized as a vector and R denotes the routing matrix. The element r_{ij} is equal to 1 if the OD pair j ($j = 1, \dots, N(N-1)$) is routed through the link l_i ($i = 1, \dots, L$). The system can be also written as:

$$[r_{i,1}, \dots, r_{i,N(N-1)}] \cdot X = y_i \,, \qquad i = 1, \dots, L, \tag{1}$$

or equivalently:

$$\sum_{n_d \in D_i} [r^d_{i,1}, \dots, r^d_{i,N(N-1)}] \cdot X = \sum_{n_d \in D_i} y^d_i \,, \quad i = 1, \dots, L, \tag{2}$$

where each element $r^d_{i,j}$ is equal to 1 iff the path of the j-th OD flow is destined to node n_d and passes through the link l_i, D_i is the set of destination nodes reached by a path that crosses the link l_i, while y^d_i is the amount of traffic flowing over the link l_i and destined at the node n_d.

Let n_S be an SDN node and $\Omega(n_S)$ the set of neighbors of n_S. As already stressed in previous section, n_S is able to provide a measure of the traffic destined to a given destination.

Referring to eq. (2), for each link connecting n_S with one of its neighbours in $\Omega(n_S)$, it is possible to get several equations, i.e., one for each internal sum in eq. (2).

More specifically, by substituting a generic node n_S with an SDN node, it is possible to add $|\bigcup_{l_i \in \Omega(n_S)} D_i|$ equations to the linear system. It is easy to see that, independently from how the sets D_i are made, the number of added equations is equal to $N-1$, since the node n_S has a path for each destination node. The new equations can be expressed as $R_{n_S} \cdot X = Y_{n_S}$ where the i-th element of the vector Y_{n_S} represents the traffic count passing through the SDN node n_S and directed to the i-th destination n_i (with $n_i \in \mathcal{N} \setminus \{n_S\}$) and each element $r_{ij}^{n_S}$ of the matrix R_{n_S} is equal to 1 if the OD pair j has n_i as destination and passes through the SDN node n_S. Finally, let us denote with $\tilde{R}_{n_S}$ and $\tilde{Y}_{n_S}$ the coefficient matrix and the vector of constant terms obtained by removing the rows corresponding to destination nodes $n_i \in \Omega(n_S)$ from R_{n_S} and Y_{n_S}, respectively.

A. Where to place SDN nodes

The traffic matrix estimation problem is caracterized by an underd-determined linear system. Considering a network with N nodes and L links, there are $\infty^{N(N-1)-rank(R)}$ solutions that satisfies $R \cdot X = Y$. As we have previously shown, by substituting some routers with SDN nodes, the linear system can be expanded with the adding of $N-1$ new equations for each SDN node. Accordingly, indicating with R^{EXT} the matrix that describe the expanded linear system, we have now $\infty^{N(N-1)-rank(R^{EXT})}$ possible solutions. In case that $rank(R^{EXT}) > rank(R)$, the presence of the SDN nodes allow a reduction of the feasible solution set that helps estimators in finding a better etimation for the vecotor X. Clearly, fixed a number M of SDN nodes, the quantity $rank(R^{EXT})$ can significantly vary by considering different sets of routers to be replaced by SDN nodes.

In particular, we found that the following theorem holds:

Theorem 1. *Given the network described by $\mathcal{N}$ and $\mathcal{L}$, let $\mathcal{W} = \{m_i\}_{i=1,\dots,M} \subseteq \mathcal{N}$ be a sub-set of M nodes substituted by SDN nodes and under the constraint of loop-free, single and shortest path routing, by adding $N-1$ equations to the routing matrix for each SDN node, the matrix*

$$R^{EXT} = [R, R_{m_1}, \cdots, R_{m_M}]^T \quad (3)$$

of the extended system of linear equations has rank:

$$rank(R^{EXT}) = L + M \cdot (N-1) - \sum_{m_i \in \mathcal{W}} |\Omega(m_i)|. \quad (4)$$

For brevity, in the sequel we refer to the last quantity with

$$\digamma(\mathcal{N}, \mathcal{W}, \mathcal{L}) = L + M \cdot (N-1) - \sum_{m_i \in \mathcal{W}} |\Omega(m_i)|. \quad (5)$$

The quantity expressed in equation 5 is exactly the number of rows of the matrix $\tilde{R}^{EXT}$.

Proof: The proof is divided in two steps: i) as first we show that $rank(\tilde{R}^{EXT}) = \digamma(\mathcal{N}, \mathcal{W}, \mathcal{L})$ and ii) then we show that $rank(R^{EXT}) = rank(\tilde{R}^{EXT})$. For simplicity, we suppose that all links have the same weight. The linear system, after the adding of $N-1$ equations to the routing matrix for each SDN node and by excluding the equations for all couple (m_S, n_i) with $m_S \in \mathcal{W}$ and $n_i \in \Omega(m_S)$ is:

$$\tilde{R}^{EXT} \cdot X = \tilde{Y}^{EXT} \quad (6)$$

where

$$\tilde{Y}^{EXT} = \begin{bmatrix} Y \\ \tilde{Y}_{m_1} \\ \vdots \\ \tilde{Y}_{m_M} \end{bmatrix}, \qquad \tilde{R}^{EXT} = \begin{bmatrix} R \\ \tilde{R}_{m_1} \\ \vdots \\ \tilde{R}_{m_M} \end{bmatrix}. \quad (7)$$

The columns of $\tilde{R}^{EXT}$ can be reordered by putting on the l-th column the OD flow corresponding to the couple of adjacent nodes connected by the l-th link, for $l = 1, \dots, L$ (consider that the links are ordered as the order of the respective rows in the matrix). Based on the hypotheses of single and shortest path[1], $\tilde{r}_{ii} = 1$ for $i = 1, \dots, L$, while $\tilde{r}_{ij} = 0$ for $i, j = 1, \dots, L$ and $i \neq j$. After the reordering, the block R of the matrix $\tilde{R}^{EXT}$ can be rewritten as:

$$R = [I_L \quad \ddot{R}] \quad (8)$$

where I_L is the unit matrix of size L and $\ddot{R}$ is the residual matrix. Then the rank of R is equal to L.

In addiction $\tilde{r}_{ij} = 0$ for $i = (L+1), \dots, \digamma(\mathcal{N}, \mathcal{W}, \mathcal{L})$ and $j = 1, \dots, L$. In fact, for each block $\tilde{R}_{m_S}$ of $\tilde{R}^{EXT}$, the elements in the first L columns cannot be equal to 1 since equations related to OD flows with a destination adjacent to m_S have been excluded in the system $\tilde{R}^{EXT} \cdot X = \tilde{Y}^{EXT}$. Then $\tilde{R}^{EXT}$ can be rewritten as

$$\tilde{R}^{EXT} = \begin{bmatrix} I_L & \ddot{R} \\ O & \hat{R} \end{bmatrix} \quad (9)$$

where O is a zero matrix, while $\hat{R}$ [2] is the residual matrix obtained by excluding the first L columns from $[\tilde{R}_{m_1}, \dots, \tilde{R}_{m_M}]^T$. $\tilde{R}^{EXT}$ is a triangular block matrix and its rank is given by:

$$rank(\tilde{R}^{EXT}) = rank(I_L) + rank(\hat{R}) = L + rank(\hat{R}) \quad (10)$$

Let us consider only the $\hat{R}$ matrix. The rows of this matrix can be reordered based on the destination of the flows, so that flows to the same destination are consecutive. Given a set of flows with the same destination n_k the following rule is used to sort them: for a couple of SDN nodes m_{S_1} and m_{S_2}, if the flow from m_{S_1} to the destination n_k passes through m_{S_2}, then the row and the column relative to the couple (m_{S_1}, n_k) must be put before the one corresponding to (m_{S_2}, n_k).[3]

[1] Single path ensures that all non zero elements of the matrix are equal to 1, while shortest path ensures that the directed path is used between adjacent nodes.

[2] $\hat{R}$ has $\digamma(\mathcal{N}, \mathcal{W}, \mathcal{L}) - L$ rows and $N(N-1) - L$ columns

[3] Nodes can be ordered following the specified rule since the loop-free hypothesis guarantees that each flow passes through a node at most once.

Then the reordered matrix of $\hat{R}$ can be written as:

$$\hat{R} = \begin{bmatrix} \hat{R}^{[1]} & O & \cdots & O & \\ O & \hat{R}^{[2]} & & \vdots & \\ \vdots & & \ddots & O & \breve{R} \\ O & \cdots & O & \hat{R}^{[N]} & \end{bmatrix} \tag{11}$$

where $\breve{R}$ is the residual matrix and each $\hat{R}^{[h]}$ is a square matrix that reports informations related to the routing from all SDN nodes to the destination node h. $\hat{R}$ is a diagonal block matrix and each block $\hat{R}^{[h]}$ is an upper triangular matrix with all element on the diagonal equal to 1, by construction. So $\hat{R}$ is upper triangular as well, with all elements on the diagonal equal to 1 and it is non-singular, then it has maximum rank (equal to the number its of rows). Therefore, from equation 10, we have $rank(\tilde{R}^{EXT}) = F(\mathcal{N}, \mathcal{W}, \mathcal{L})$. This concludes the first part of the proof.

Now we show that each excluded equation in the extended system is linearly dependent to the equations included in the system described by the matrix $\tilde{R}^{EXT}$. Let us fix a node $m_S \in \mathcal{W}$ and choose an adjacent node $n_k \in \Omega(m_S)$. Let l_i be the link connecting the nodes m_S and n_k. Then, by using the same notation of eq. (2), the corresponding excluded equation is $[r^k_{i,1}, \ldots, r^k_{i,N(N-1)}] \cdot X = y^{n_k}_i$. By subtracting from eq. (1) the eq. (2) and isolanting the term referred to node n_k as destination, we have

$$\begin{aligned}&[r^k_{i,1}, \ldots, r^k_{i,N(N-1)}] = \\ &= [r_{i,1}, \ldots, r_{i,N(N-1)}] - \sum_{n_d \in D_i - \{n_k\}} [r^d_{i,1}, \ldots, r^d_{i,N(N-1)}]\end{aligned} \tag{12}$$

$$y^{n_k}_i = y_i - \sum_{n_d \in D_i - \{n_k\}} y^d_i \tag{13}$$

The equalities reported in eqs. (12) and (13) show that each excluded equation can be written as a linear combination of the ones not excluded. Then must be $rank(R^{EXT}) = F(\mathcal{N}, \mathcal{W}, \mathcal{L})$. [q.e.d.]

A first interesting result that comes out from the theorem is that nodes with low degree are good candidates to be replaced with an SDN nodes, since they allow to increase the rank of the expanded system. Looking at equation 4 it can be seen that if all nodes are SDN, then the rank of R^{EXT} and the system has only one solution. Finally, the rank of the routing matrix is equal to L in case of shortest path routing.

IV. Numerical results

In this section we provide the performance evaluation of a traffic matrix estimation method enhanced by the information provided by SDN nodes. We first describe the datasets used in the analysis, then we discuss the use of a specific traffic matrix estimation algorithm, and finally we evaluate the performance behavior for different SDN nodes placement criteria.

A. Datasets

In this work we considered three network topologies, Abilene, Nobel and Brain. The topologies and the related real traffic data are provided by the SNDLib project [20].

The Abilene is the backbone network interconnecting universities, companies, and government laboratories in USA; it consists of 12 nodes and 30 links. Nobel is the German Research Network and consists of 17 nodes and 26 links. The BRAIN research network of Germany is composed of 9 core nodes and 152 access nodes; in our analysis we consider the simplified network of 9 nodes and 28 links where each access node has been merged in the adjacent core node.

B. The Estimation Algorithm

A generic estimation algorithm can exploit the extra information provided by SDN nodes to enhance its estimation capability. This extra information is independent of the algorithm used, as stated by Eq. 1, even if each algorithm can exploit the extra-information differently. The scope of this work is not to define the best estimation algorithm, but to verify two main features: i) to show that the extra information provided by SDN nodes improves the traffic estimation, and ii) to verify the results pointed out in Theorem 1 in real cases, i.e., that replacing low degree nodes provides better performance with respect to replacing high-degree ones. In our assessment, we consider the Tomogravity algorithm [6] which is widely recognized as a robust method to estimate the OD flows.

C. Performance Analysis

As indicator of the accuracy of the estimation, we consider the Mean Relative Error (MRE):

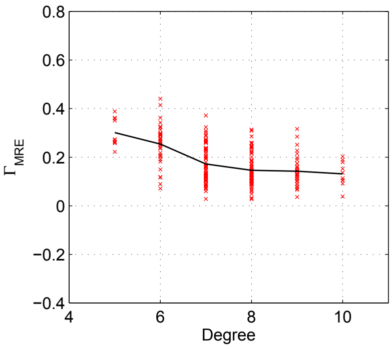
$$MRE = \frac{1}{N(N-1)} \sum_{k=1}^{N(N-1)} \left| \frac{x_k - \hat{x}_k}{x_k} \right| \tag{14}$$

where x_k is the true traffic demand of the k-th flow while $\hat{x}_k$ is the corresponding estimated value. In order to highlight the improvements on the MRE by the exploitation of the SDN extra information, we define the following parameter:

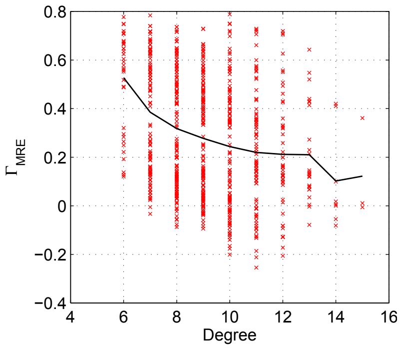
$$\Gamma_{MRE} = [MRE^0 - MRE(n)]/MRE^0 \tag{15}$$

where MRE^0 is the MRE with no SDN nodes, while MRE^n is the MRE achieved when n routers are replaced with n SDN nodes. When Γ_{MRE} is equal to 1, it means that all the OD pairs have been correctly estimated.

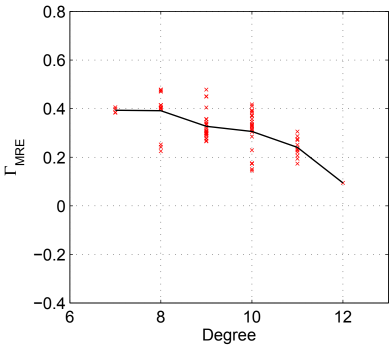
The first analysis we propose consists in evaluating the MRE achieved by substituting a subset of routers with SDN nodes. The characterization of the nodes subset is based on its overall degree, i.e., the sum of the degrees of the nodes belonging to the chosen subset. This choice is motivated by the relationship among the extra-information and the node degree, as described in eq. (5). In the following we consider a subset of three SDN nodes. Similar results are obtained for different subset sizes. In Figure 1, the Γ_{MRE} parameter for all possible triples of SDN nodes as a function of their degree is shown. The first interesting result is that, for the considered topologies, Γ_{MRE}



(a) Abilene

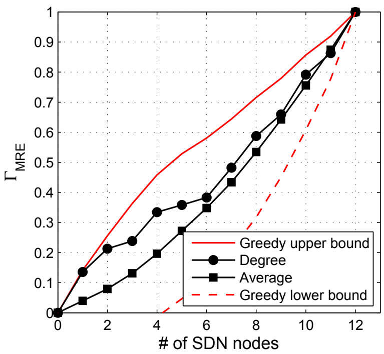


(b) Nobel

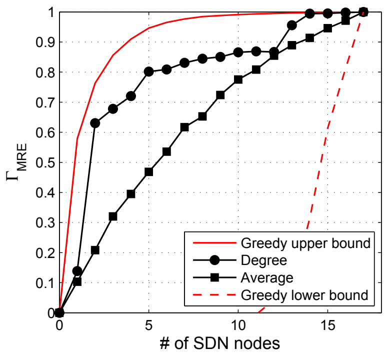


(c) Brain

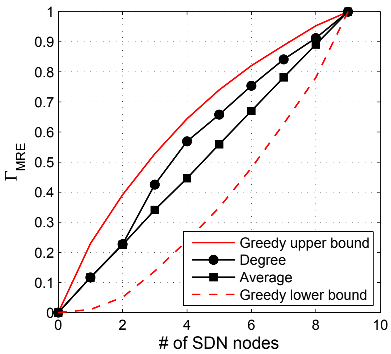
Fig. 1: Analysis of Γ_{MRE} considering triple of SDN nodes.



(a) Abilene



(b) Nobel



(c) Brain

Fig. 2: Analysis of Γ_{MRE} considering different sorting criteria.

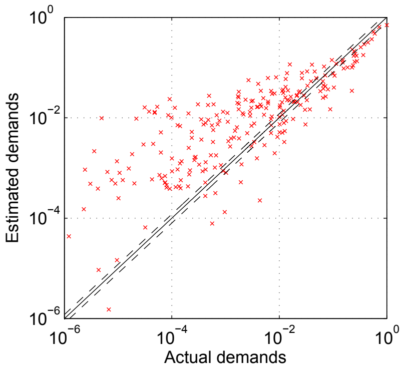
decreases on average as the degree increases. This confirms the outcome of Theorem 1: nodes with low degree entail an higher rank of the matrix R^{EXT}. Moreover, the results in Figure 1b show that in some cases the Γ_{MRE} assumes negative values, i.e., the MRE with no SDN nodes is lower than the MRE considering three SDN nodes. This is mainly due at the Tomogravity algorithm, that is not able to exploit the available extra information of SDN nodes in such cases.

The second analysis is shown in Figure 2, where different SDN nodes placement criteria are evaluated. The behavior of Γ_{MRE} as a function of the number of SDN nodes inserted is reported. The placement criteria considered are:

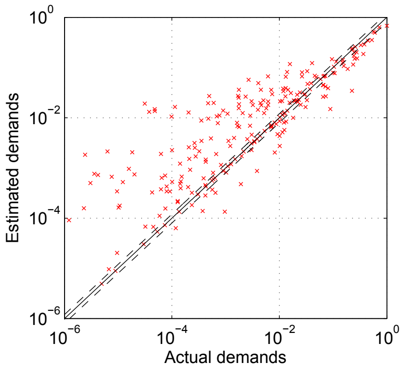
- *Greedy Upper Bound*: the SDN nodes list is built in a greedy fashion, i.e.m iteratively adding the node that minimizes the MRE;
- *Greedy Lower Bound*: the SDN nodes list is built in a greedy fashion, i.e., iteratively adding the node that maximizes the MRE;
- *Degree*: the SDN nodes list is built in a heuristic way, on the basis of nodes degree, i.e., iteratively adding the node with lowest degree; in the case of nodes with the same degree, decreasing order of crossing traffic (either injected and transit) is used;
- *Average*: the SDN nodes list is built in a random way.

The results reported in Figure 2 show that a proper placement criterion allows to achieve a more than linear improvement in traffic matrix estimation. The solution space is represented by the area bounded by the the *Greedy Upper Bound* and the *Greedy Lower Bound* solutions. The *Degree* curves are almost over the bisector, particularly in Figure 2b. A further result shown in Figure 2 is that the *Degree* heuristic has always better performance with respect to the *Average* case, confirming that node degree is a good parameter for the SDN node placement as stated by Theorem 1. The results obtained for the Nobel topology also highlights that with the introduction of few SDN nodes, a great estimation improvement is gained, e.g., with two SDN nodes the *Degree* heuristic allows to improve the estimation of more than 60%.

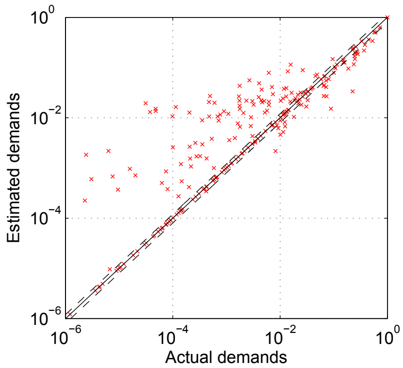
The last analysis we propose is presented in Figure 3, where a visual representation of the estimation improvement is shown. Each point of the graphs represents the ratio between the real value of an OD pair traffic and its estimated value. If a flow is correctly estimated, then the relative point will fall on the bisector. If the point falls in the area between the two



(a) no SDN node



(b) 3 SDN nodes



(c) 8 SDN nodes

Fig. 3: Estimated values VS Real values.

dashed lines, then it means that the estimation error is at most 20%. The analysis is reported for the Nobel topology in case of: a) no SDN nodes (Figure 3a); b) 3 SDN nodes (Figure 3b); c) 8 SDN nodes (Figure 3c). Nodes are chosen according to the *Degree* criterion. The results highlight that moving from no SDN nodes to 3 SDN nodes and to 8 SDN nodes, a larger number of flows are correctly estimated.

V. Conclusions

We have re-visited the statement of the traffic matrix estimation problem in a communication network in an SDN evolutionary approach, where few SDN enabled nodes are introduced. By developing a basic theory, we have elaborated on the criteria to obtain the most convenient placement of SDN functionalities as for the accuracy of the matrix estimation. It turns out that nodes with the least degree (least number of outgoing links) are the best choice.

Further work is required to dig into the connection between topological and traffic characteristics of the network, since both of these aspect appear to be relevant to improve the accuracy of the estimate. We took a general approach, without reference to specific applications of the estimated matrix. In case an application is given, specific performance metrics could be defined and fine tuning of estimation process can be elaborated, taking into account the whole design loop that the traffic matrix estimation is a step of.

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