INT-FC: Low-Overhead In-band Network Telemetry via Flow-Conservation-Constrained Link Recovery in Fat-Tree Data Centers

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***Abstract*—In-band Network Telemetry (INT) enables fine-grained link visibility in data center networks, but directly measuring all switch-to-switch links in each measurement period incurs non-negligible overhead. This paper proposes Flow-Conservation-guided In-band Network Telemetry (INT-FC), a low-overhead INT framework for Fat-tree networks. INT-FC exploits the node-level conservation property of additive flow-volume counters at aggregation and core switches, and formulates link monitoring as a conservation-constrained recovery problem. It selects directly measured links through a recoverability-aware sampling strategy and reconstructs skipped link traffic via iterative conservation-based recovery. INT-FC targets additive counters, such as byte count and packet count, while excluding delay- and queue-related metrics that do not satisfy flow conservation. Evaluation on Fat-tree settings shows that, compared with the INT-path full-coverage probing baseline, INT-FC reduces direct link measurements by up to 18.75% and achieves lower telemetry metadata overhead under the evaluated settings while preserving complete switch-to-switch link-state reconstruction.**

***Index Terms*—In-band Network Telemetry, Flow Conservation, Fat-tree, Link Traffic Recovery, Low-Overhead Monitoring.**

I. Introduction

Fine-grained link traffic monitoring is essential for data center network operations, such as congestion diagnosis, traffic imbalance detection, and traffic engineering [1]. In-band Network Telemetry (INT) provides fine-grained in-network visibility by allowing packets to carry telemetry metadata [2]. However, achieving complete link-level visibility usually requires extensive telemetry collection. A straightforward full-coverage INT strategy needs to directly measure all switch-to-switch directed links in every measurement period, introducing non-negligible overhead in probe traffic, telemetry headers, switch-side state access, and control-plane data processing.

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Prior studies have improved monitoring efficiency from different perspectives, including software-defined measurement resource allocation [3], telemetry framework design [4], programmable data-plane measurement [5], and packet-level telemetry systems [6]. For network-wide INT, INT-path [7] plans non-overlapped probe paths to cover the entire network, but it still follows a full-coverage principle in which all switch-to-switch links are directly covered. Therefore, existing studies do not fully address whether some directed links can be skipped from direct INT measurement and later reconstructed.

This paper exploits a structural opportunity in Fat-tree data center networks. Fat-tree topologies are widely used because of their scalability and path diversity [8]. In such topologies, aggregation and core switches mainly act as forwarding nodes. For additive flow-volume counters, such as byte count and packet count, their incoming and outgoing traffic should be approximately balanced under lossless forwarding and synchronized measurement periods. Thus, when all but one directed link in a conservation equation are known, the remaining link traffic can be inferred. Flow conservation has long been used in network tomography to infer traffic information from indirect observations [9]. Later studies further summarized how structural relationships support inference from partial network measurements [10]. TomoGravity also demonstrated that link-load measurements can be used to estimate large-scale traffic matrices [11]. However, the potential of flow conservation for reducing direct INT measurements over switch-to-switch links remains underexplored.

Motivated by this observation, we propose Flow-Conservation-guided In-band Network Telemetry (INT-FC), a low-overhead framework for link traffic recovery in Fat-tree networks. INT-FC models switch-to-switch traffic as directed link variables, constructs a node-arc incidence matrix to represent conservation constraints, and partitions the directed link set into a directly measured set M and a recoverable unmeasured set U. Probe paths are planned only for links in M, while links in U are recovered through iterative conservation-based recovery. In this way, INT-FC reduces direct INT measurements while preserving complete switch-to-switch link traffic reconstruction. This capability is useful for traffic management systems that rely on timely data center traffic information [12]. Congestion-aware load balancing in data centers also benefits from accurate and timely network state information [13].

The main contributions are summarized as follows:

- We formulate low-overhead INT-based link monitoring in Fat-tree networks as a flow-conservation-constrained recovery problem over directed switch-to-switch links.
- We design INT-FC, a recoverability-aware partial-coverage INT framework that selects directly measured links and recoverable unmeasured links according to node-level flow conservation. We further develop a probe-path-based measurement procedure and an iterative conservation-based recovery algorithm to support complete link-state reconstruction.
- We evaluate INT-FC against an INT-path full-coverage probing baseline on Fat-tree settings. Experimental results show that INT-FC reduces direct link measurements by up to 18.75% and achieves lower telemetry metadata overhead under the evaluated settings while preserving complete switch-to-switch link-state reconstruction.

II. Related Work and Motivation

Existing low-overhead INT studies mainly reduce telemetry cost at the packet or flow level. PINT represents probabilistic telemetry and bounds the telemetry information carried by each packet through probabilistic encoding [14]. Selective INT reduces monitoring overhead by collecting telemetry only for selected packets or flows [15]. Runtime-programmable selective telemetry supports flexible event- or policy-based INT collection [16]. Deterministic and probabilistic lightweight INT further reduces P4-INT transmission overhead by distributing telemetry information across packets or inserting telemetry items probabilistically [17]. These methods reduce the amount of telemetry data carried or reported, but they do not exploit structural relationships among switch-to-switch link traffic variables.

Sampling-and-recovery methods reduce telemetry collection by inferring missing values from partial observations. INT spatial sampling reconstructs unmeasured telemetry samples by exploiting spatial correlation among monitored links [18]. Recent spatial sampling studies further provide theoretical and experimental results for reducing INT overhead through partial observations [19]. Matrix-completion-based telemetry methods, such as INT-MC [20], model network-wide link metadata as a partially observed matrix and recover missing link states based on low-rank assumptions. Flow conservation has also been widely used in traffic matrix estimation and network tomography [9]. However, existing studies do not address how to select switch-to-switch links for direct INT measurement and recover skipped link traffic in Fat-tree data center networks. This gap motivates us to revisit the structural properties of Fat-tree networks and investigate whether flow conservation can be used to support low-overhead INT measurement.

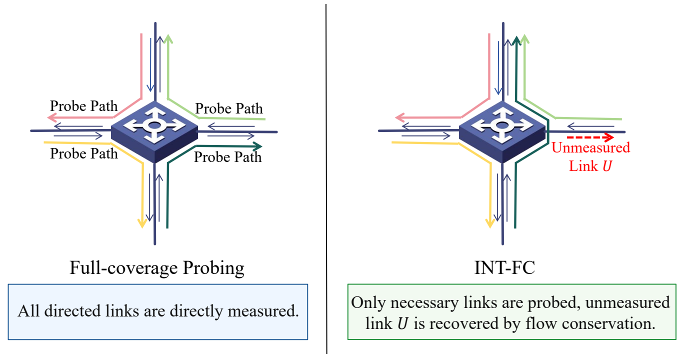


Fig. 1: Motivating example of full-coverage probing and INT-FC.

The motivation of INT-FC comes from node-level flow conservation in Fat-tree networks. Under lossless forwarding and synchronized measurement periods, the incoming and outgoing flow-volume counters of aggregation and core switches are approximately balanced. Thus, when all but one directed link in a conservation equation are known, the remaining link traffic can be inferred without direct INT measurement.

As illustrated in Fig. 1, full-coverage probing directly measures all directed links around the switch, whereas INT-FC leaves a recoverable link unmeasured and obtains its value through flow conservation. This example shows that complete switch-to-switch link traffic reconstruction does not always require complete direct measurement.

III. Design of INT-FC

This section presents the design of INT-FC. We first introduce the network model, the directed link traffic representation, the conservation constraints, and the link recovery problem. We then describe the overall workflow, the recoverability-aware link sampling strategy, the probe path planning procedure, and the iterative conservation-based recovery algorithm.

A. Preliminaries and Problem Formulation

We consider the switch-to-switch part of a Fat-tree data center network, which is modeled as a directed graph

$$G = (V, E), \tag{1}$$

where V denotes the set of switches and E denotes the set of directed switch-to-switch links. Each physical link between two switches u and v is represented by two directed links, i.e., $e_{u\to v}$ and $e_{v\to u}$, since traffic in the two directions can be different.

INT-FC focuses on directed link traffic states rather than node-level traffic volumes. For a directed link $e_{u\to v}$, its traffic value during measurement period t is denoted by $x_{u\to v}(t)$, which is defined as the value of a selected TX flow-volume counter on the egress port of switch u toward switch v. Thus, the direction of a link variable is determined by the source switch and its egress port. The primary telemetry objects considered by INT-FC are additive flow-volume counters, such as byte count and packet count. The conservation model is applied independently to each counter type; for brevity, $x_e(t)$ denotes the value of one selected additive counter in the following formulation. Delay- and queue-related metrics are outside the scope of this model because they do not satisfy additive flow conservation.

Let $x_e(t)$ denote the traffic value of directed link $e \in E$, and let $\mathbf{x}(t)$ be the vector of all directed link traffic values. We use $V_c \subseteq V$ to denote the set of switches used for conservation modeling. In this paper, V_c includes aggregation and core switches, and is defined as

$$V_c = V_{\text{agg}} \cup V_{\text{core}}. \tag{2}$$

Edge switches are excluded from conservation modeling because their host-facing ports act as external traffic sources and sinks. Nevertheless, edge–aggregation links are still included in the monitored directed link set E.

For each switch $v \in V_c$, let $\delta^-(v)$ and $\delta^+(v)$ denote the sets of incoming and outgoing directed links associated with v, respectively. Under lossless forwarding and synchronized measurement periods, the node-level conservation constraint for additive flow-volume counters at aggregation and core switches is expressed as

$$\sum_{e\in\delta^-(v)} x_e(t) - \sum_{e\in\delta^+(v)} x_e(t) = 0, \quad v \in V_c. \tag{3}$$

To represent all conservation constraints compactly, INT-FC constructs a node-arc incidence matrix $\mathbf{A} \in \mathbb{R}^{|V_c|\times|E|}$, where each row corresponds to a conservation switch and each column corresponds to a directed link. The matrix element is defined as

$$A_{v,e} = \begin{cases} 1, & e \in \delta^-(v), \\ -1, & e \in \delta^+(v), \\ 0, & \text{otherwise}. \end{cases} \tag{4}$$

Then the conservation constraints can be written as

$$\mathbf{A}\mathbf{x}(t) = \mathbf{0}. \tag{5}$$

Here, $|E|$ represents the number of directed link variables, rather than the number of directed port incidences appearing in the conservation equations.

In each measurement period, INT-FC partitions the directed link set into two disjoint subsets, denoted by M and U. This partition is given by

$$E = M \cup U, \quad M \cap U = \emptyset, \tag{6}$$

where M is the set of directly measured links and U is the set of unmeasured links to be recovered. The measured links in M are covered by INT probe paths, while the traffic values of links in U are inferred from conservation constraints.

Accordingly, Eq. (5) can be decomposed as

$$\mathbf{A}_M\mathbf{x}_M(t) + \mathbf{A}_U\mathbf{x}_U(t) = \mathbf{0}, \tag{7}$$

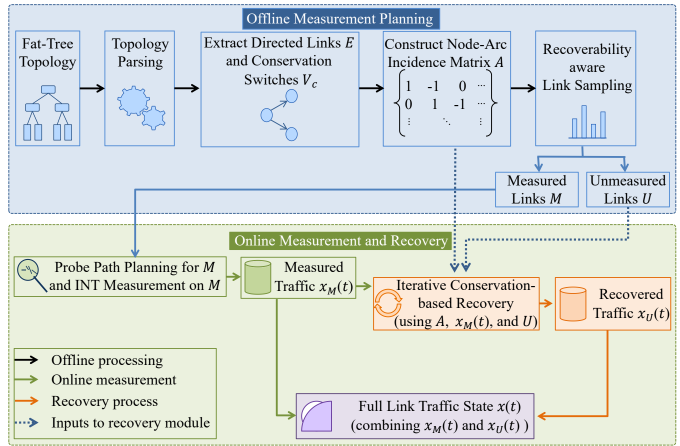


Fig. 2: Overall framework of INT-FC.

where $\mathbf{A}_M$ and $\mathbf{A}_U$ are the column submatrices associated with M and U, respectively. Since $\mathbf{x}_M(t)$ is obtained by direct INT measurement, the unknown traffic satisfies

$$\mathbf{A}_U\mathbf{x}_U(t) = -\mathbf{A}_M\mathbf{x}_M(t). \tag{8}$$

An unmeasured link set U is recoverable if $\mathbf{x}_U(t)$ can be uniquely determined from Eq. (8). A sufficient algebraic condition for unique recovery is

$$\text{rank}(\mathbf{A}_U) = |U|. \tag{9}$$

This full-column-rank condition ensures that the unmeasured link variables are uniquely identifiable from the conservation equations. If this condition does not hold, multiple unmeasured traffic vectors may satisfy the same measured values and conservation constraints.

In implementation, INT-FC adopts a peeling-style recoverability test as a practical sufficient test. A candidate unmeasured set is accepted only if its links can be recovered by repeatedly applying local conservation equations that contain exactly one unknown link.

The measurement planning problem of INT-FC is to reduce the number of directly measured links while preserving recoverability. It is formulated as

$$\min_{M\subseteq E} \quad |M|, \tag{10}$$

$$\text{s.t.} \quad U = E \setminus M, \tag{11}$$

$$\text{rank}(\mathbf{A}_U) = |U|. \tag{12}$$

This formulation captures the main goal of INT-FC: directly measuring only a subset of directed links and recovering the remaining links through flow conservation, thereby reconstructing the complete switch-to-switch directed link traffic state.

B. Overview

Fig. 2 illustrates the overall workflow of INT-FC, which consists of offline measurement planning and online measurement and recovery. In the offline stage, the control plane parses

Algorithm 1 Recoverability-aware Link Sampling

Input: Directed link set E, incidence matrix $\mathbf{A}$
Output: Measured link set M, recoverable unmeasured link set U

Initialize $M \leftarrow E$, $U \leftarrow \emptyset$
Generate a candidate link order $\pi(E)$
for each link $e \in \pi(E)$ **do**
    $M' \leftarrow M \setminus \{e\}$
    $U' \leftarrow U \cup \{e\}$
    if RECOVERABILITYTEST($\mathbf{A}, M', U'$) = true **then**
        $M \leftarrow M'$
        $U \leftarrow U'$
    end if
end for
return M, U

the Fat-tree topology, extracts the directed link set E and conservation switch set V_c, constructs the node-arc incidence matrix $\mathbf{A}$, and performs recoverability-aware link sampling to obtain the measured set M and recoverable unmeasured set U. INT probe paths are then planned to cover the links in M.

In the online stage, probes collect flow-volume counters only on links in M, forming $\mathbf{x}_M(t)$ for each measurement period. The control plane recovers $\mathbf{x}_U(t)$ using $\mathbf{A}$, U, and $\mathbf{x}_M(t)$, and combines the measured and recovered values to obtain the complete switch-to-switch directed link traffic state $\mathbf{x}(t)$.

C. Recoverability-aware Link Sampling

Given the conservation matrix $\mathbf{A}$, INT-FC determines which directed links can be skipped while preserving recoverability. A random selection may place multiple unknown links in the same conservation equation and make them non-identifiable. Therefore, INT-FC adopts a recoverability-aware greedy sampling strategy, as summarized in Algorithm 1.

The algorithm starts from full measurement, i.e., $M = E$ and $U = \emptyset$. It then scans candidate links according to an ordered sequence $\pi(E)$. For each link e, INT-FC tentatively moves it from M to U and accepts this move only if the updated unmeasured set remains recoverable; otherwise, e is kept in M.

The recoverability test follows the same principle as the later conservation-based recovery procedure. A candidate set U' is accepted if all links in U' can be inferred by iteratively finding conservation equations with exactly one unknown link. In this paper, $\pi(E)$ is implemented using a topology-based order, so that the benefit of flow conservation can be evaluated without relying on historical traffic statistics. Although this greedy strategy does not guarantee a globally minimum measured link set, it avoids exhaustive search and ensures that skipped links remain recoverable by the subsequent recovery algorithm. Since Fat-tree topologies are usually stable, the sampling process can be performed offline and reused across measurement periods.

D. Probe Path Planning for Measured Links

After the measured link set M is obtained, INT-FC realizes direct measurements through probe-based INT measurement. Let $\mathcal{P}$ denote the candidate set of feasible probe paths, and let $C(p) \subseteq E$ be the set of directed switch-to-switch links traversed by path p. The objective is to select a path subset $\mathcal{P}_M \subseteq \mathcal{P}$ that covers all measured links. This coverage condition is given by

$$M \subseteq \bigcup_{p \in \mathcal{P}_M} C(p). \tag{13}$$

This problem can be viewed as a set-cover problem over M. INT-FC adopts a greedy path-cover strategy that repeatedly selects the path covering the largest number of currently uncovered measured links per unit cost until all links in M are covered. During online monitoring, probes are sent along the selected paths in $\mathcal{P}_M$ and collect telemetry metadata only for links in M. If a probe path also traverses a link in U, the corresponding telemetry item is skipped or ignored.

E. Conservation-based Link Recovery

After probes traverse the selected path set $\mathcal{P}_M$, the control plane obtains the measured traffic vector $\mathbf{x}_M(t)$ for links in M. The remaining task is to recover the traffic values of links in U using the conservation constraints at aggregation and core switches.

For a conservation switch v, if its conservation equation contains exactly one unknown link $e \in U$, all other link values in this equation are already known. Therefore, the value of link e can be recovered as

$$x_e(t) = -\frac{\sum_{j \neq e} A_{v,j} x_j(t)}{A_{v,e}}, \tag{14}$$

where $A_{v,e} \in 1, -1$ for any directed link appearing in the conservation equation.

Based on Eq. (14), INT-FC performs iterative conservation-based recovery. It repeatedly searches for a conservation equation with exactly one unknown link, recovers that link, and removes it from the unmeasured set U. Each recovered link becomes a known value and may further enable the recovery of other links in subsequent iterations. If all links in U are recovered, INT-FC obtains the complete switch-to-switch link traffic state by combining $\mathbf{x}_M(t)$ and $\mathbf{x}_U(t)$; otherwise, the current measurement plan is regarded as insufficient under the adopted recoverability criterion.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

We evaluate INT-FC on Fat-tree topologies and compare it with INT-path, which serves as a full-coverage probing baseline. Following the network-wide coverage principle of INT-path, the baseline directly covers all switch-to-switch directed links in each measurement period. Different from this full-coverage design, INT-FC directly measures only the selected link set M and recovers the unmeasured link set U through flow conservation, aiming to reduce direct INT measurements while preserving complete link-state reconstruction.

A. Experimental Settings

The evaluation is conducted on multiple Fat-tree settings with $k = 4, 6, 8, 10, 12$, and 16. These settings cover both small-scale prototype validation and larger-scale performance evaluation. The $k = 4$ Fat-tree contains 20 switches, 16 hosts, and 64 directed switch-to-switch links, while larger Fat-tree settings contain more switches, hosts, and directed links according to the standard Fat-tree structure. Following the design of INT-FC, aggregation and core switches are used to construct conservation constraints, while edge switches are excluded due to host-facing traffic injection and absorption. The evaluated telemetry variables are additive flow-volume counters, such as byte count and packet count.

For telemetry metadata overhead, we follow the INT-path packet format, where each INT metadata item occupies $s_{\text{INT}} = 22$ bytes. The probe sending rate is set to $f = 100$ pps. For a method that directly collects telemetry metadata from $|M|$ directed links in one measurement period, the telemetry metadata bandwidth overhead is calculated as

$$B = |M| \cdot s_{\text{INT}} \cdot 8 \cdot f/10^6, \tag{15}$$

where B is measured in Mbps.

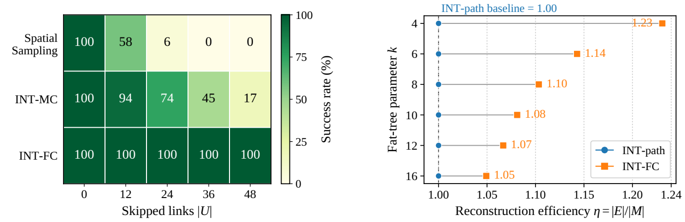
B. Recoverability and Reconstruction Efficiency

Fig. 3 evaluates INT-FC from the perspectives of recovery success and reconstruction efficiency. To examine whether complete link-state reconstruction can be preserved under partial observation, we conduct experiments with different skipped-link budgets and compare INT-FC with two representative sampling-and-recovery baselines. The first baseline follows spatial-sampling-based INT methods [18], which reduce telemetry overhead by sampling partial observations and recovering missing values based on spatial correlations. The second baseline follows the matrix-completion-based telemetry recovery principle of INT-MC, which models network-wide link metadata as a partially observed matrix and recovers missing link states using low-rank structures. For a fair comparison, all baselines are evaluated under the same skipped-link budgets, and a trial is counted as successful only when all skipped directed links are reconstructed.

The results in Fig. 3(a) show that existing sampling-and-recovery baselines become less reliable as the skipped-link budget increases. This is because correlation- or low-rank-based recovery does not explicitly enforce switch-level flow-conservation constraints, and thus cannot always guarantee complete reconstruction of skipped directed links. In contrast, INT-FC maintains complete recovery across all tested budgets by accepting only recoverable skipped links during the measurement planning stage. This result confirms the importance of incorporating recoverability awareness into link selection.

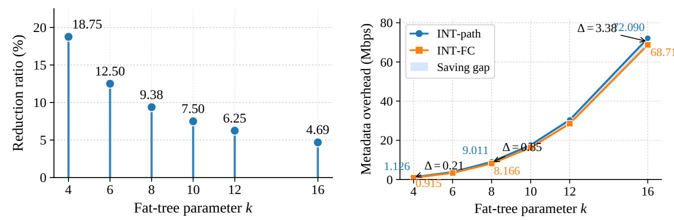
Fig. 3(b) further reports the link-state reconstruction efficiency, defined as

$$\eta = \frac{|E|}{|M|}, \tag{16}$$



(a) Recovery success rate. (b) Reconstruction efficiency.

Fig. 3: Recoverability and reconstruction efficiency of INT-FC.



(a) Measurement reduction ratio. (b) Metadata bandwidth overhead.

Fig. 4: Scalability and telemetry metadata overhead of INT-FC.

where $|E|$ is the total number of directed switch-to-switch links and $|M|$ is the number of directly measured links. INT-path has $\eta = 1.00$ because each reconstructed link state is obtained from direct measurement. By contrast, INT-FC achieves higher efficiency across all Fat-tree scales, indicating that conservation-based recovery enables each directly measured link to support more complete network-wide link-state reconstruction.

C. Scalability of Measurement Reduction and Metadata Overhead

Fig. 4 evaluates the scalability of INT-FC under different Fat-tree scales. For each Fat-tree setting, we first run the recoverability-aware sampling procedure to obtain the directly measured link set M and the recoverable unmeasured link set U. Based on the resulting link partition, Fig. 4(a) reports the measurement reduction ratio, computed as $|U|/|E|$. INT-FC consistently reduces the number of directly measured links. The reduction ratio decreases from 18.75% at $k = 4$ to 4.69 % at $k = 16$, because the number of recoverable links grows with the number of conservation switches, while the total number of directed links grows faster with the network scale.

Using the same measured link set M, we further calculate the telemetry metadata bandwidth overhead according to Eq. (15). Fig. 4(b) compares the resulting metadata overhead of INT-path and INT-FC. Since INT-path directly covers all directed links, its overhead is proportional to $|E|$, whereas INT-FC only collects metadata from $|M|$. As a result, INT-FC reduces the overhead from 1.126 Mbps to 0.915 Mbps at $k = 4$, from 9.011 Mbps to 8.166 Mbps at $k = 8$, and from 72.090 Mbps to 68.710 Mbps at $k = 16$. The shaded gap between the two curves indicates that the absolute metadata bandwidth saving increases with the network scale.

V. Conclusion

This paper proposed Flow-Conservation-guided In-band Network Telemetry (INT-FC), a low-overhead link traffic monitoring framework for Fat-tree data center networks. INT-FC exploits node-level flow conservation at aggregation and core switches to reduce direct measurements over switch-to-switch directed links. It partitions links into a directly measured set and a recoverable unmeasured set, plans probe paths to cover the measured links, and reconstructs skipped links through iterative conservation-based recovery. Experimental results on Fat-tree settings with different scales show that, compared with the INT-path full-coverage probing baseline, INT-FC reduces direct link measurements by up to 18.75% while preserving complete switch-to-switch link-state reconstruction. Since telemetry metadata overhead is proportional to the number of directly measured links, INT-FC also achieves lower metadata bandwidth overhead than INT-path under the evaluated settings.

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