On Distributed Optimization Paradigm for In-Network Processing to Achieve Quality of Information

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***Abstract*—We propose a distributed framework for optimizing in-network processing (INP) for quality of Information (QoI). In an information network consisting of different types of communication devices equipped with various types of sensors, it is inevitable that a huge amount of data will be generated. Storing, processing and transmitting this very large volume of data are very challenging, if not impossible. INP provides a platform by processing (e.g., fusing, aggregating or compressing) the data along the transmission routes. This reduces the volume of transmitted data, therefore optimizing utilization of the network resources, namely energy and bandwidth. However, processing sensor data often results in an imprecise outcome such as irrelevancy, incompleteness, etc. Therefore, besides characterizing the QoI in these systems, which is important, it is also crucial to consider the effect of further data processing on the measured QoI associated with each specific piece of information. We formulate the QoI-aware INP problem as a non-linear optimization problem with the aim of satisfying a QoI requirement as specified by an end-user. We introduce a distributed framework that facilitates controlling INP via considering the level at which a system can process information without violating or deteriorating QoI.**

I. Introduction

In-Network Processing (INP) is a common technique, which enables and support possible solutions for optimising the utilization of networks resources such as bandwidth and energy. Initially, INP aims to aggregate (e.g., compress, fuse and average) and route data from different sources with the objective of reducing resource consumption, particularly energy, thereby increasing network lifetime [1]. While INP can optimize network resource usage, it is very fundamental to consider how such data processing affects the Quality of Information (QoI) for the end-user. The reason behind this idea is that information is a main resource of many decision-making/ controlling applications. Therefore, information quality (e.g., accuracy, timeliness or completeness) can affect the quality of the decision or controlling process in these applications and unquestionably, processing information can decrease or increase the quality of information [2].

In the most recent work, Edwards et. al. [3] present the notion of QoI-aware networking. They propose that QoI-aware networking algorithm must consider how data is transformed into information and the impact that the network may have on this transformation. [4] provides a centralized approach for network delivery and timeliness with the certain information accuracy. [5] points out that delivered QoI is a function of attributes that sources provide as a result of observing the events and channel attributes, and proposed a centralized transmission schedule to maximize the utility function of QoI. However, the excising work does not consider INP. As for distributed approaches, Eswaran et. al. [6] apply the network utility maximum (NUM) framework to dynamically determine the optimal compression and fusion factors for INP and the nodes in a path as the optimal places for performing data processing. A common assumption among in the existing NUM work is the concavity of the utility functions, which may not be valid for many communication networks and applications [7].

II. Problem formulation

Since the degree at which a node can aggregate its received data is one of the main determining factors for QoI [2], we aim to introduce a distributed framework that can determine the optimal degree of aggregation at each node, while meeting the QoI required by the end-user.

We assume that a data aggregation tree is formed among all nodes in the network after the user requests information from the network.The root node, *r*,of the tree is responsible for delivering the required information to the end-user. It is assumed that only leaves nodes generate data and the rest of the nodes in the tree process and forward data toward the root node. Furthermore, we assume data generated in the information network has some degree of redundancy due to spatial and temporal correlations among sensors. Therefore, it is possible to aggregate data as a means to optimize utilization of network resources. We define the ratio of the volume of aggregated data to that of all data at each node received from its children nodes as the *data reduction rate* denoted by δ between 0 and 1.

A. Global Optimization

We formulate the problem of QoI-awre INP as a non-linear optimization problem. Specifically, our goal is to choose the data reduction rates at all nodes involved in the aggregation process in order to minimize the total cost for the whole aggregation tree, while ensuring that the level of QoI at the end-user exceeds a specified QoI threshold. The global optimisation problem (to be referred as the GO problem) is as follows:

$$\begin{aligned} \min_{\boldsymbol{\delta}} \quad & \sum_{\mathrm{i}=1}^{\mathrm{N}} f_i(\delta_i, y_i) \\ \text{s.t.} \quad & q_r(\delta_r, y_r) \geq \gamma \end{aligned} \quad , \tag{1}$$

where *N* is the total number of nodes in the data aggregation tree. $f_i(\delta_i, y_i)$ is the cost function of node i, which is a function of the volume of input data y_i received from its children nodes and the data reduction rate δ_i at node i. $\boldsymbol{\delta}$ is a vector of reduction rates for all nodes. $q_r(\delta_r, y_r)$ specifies the QoI function. Since the root node, *r*, is responsible for delivering the required information to the end-user, the QoI constraint is associated with the root node. γ indicates the QoI requirement threshold specified by the end-user. Even though the problem has only a single QoI constraint associated with the root node, the data reduction rate must be chosen optimally at every node so that the QoI constraint for the end-user can be satisfied. Since it is assumed that only leaf nodes generate data, we have

$$y_i = \sum_{\mathrm{j} \in \mathrm{C_i}} \delta_j y_j \quad for \quad i = 1 : N \quad , \tag{2}$$

where C_i denotes the set of children nodes of node i.

Substituting (2) into the objective function and the inequality constraint in (1) reveals that inherently, the GO problem is a polynomial problem.

III. Proposed Solution

Following the assumptions made in [8], let $f_i(\delta_i, y_i)$ and $q_r(\delta_r, y_r)$ be defined as follows. Let f_i denote the total energy consumption of node i as

$$f_i = e_{iR} + e_{iC} + e_{iT}, \tag{3}$$

where e_{iR}, e_{iC} and e_{iT} denote the energy spent in receiving, aggregating (computing) and transmitting data by node i, respectively. Then, we assume

$$e_{iR} = f(y_i) = \epsilon_R y_i. \tag{4}$$

$$e_{iT} = g(y_i, \delta_i) = \epsilon_T y_i \delta_i, \tag{5}$$

$$e_{iC} = k(y_i, \delta_i) = \epsilon_C y_i l_i(\delta_i), \tag{6}$$

$$q_r = y_r \delta_r, \tag{7}$$

where, ϵ_R, ϵ_T and ϵ_C are the energy consumed in receiving, transmitting and processing one unit of data respectively. $l_i(\delta_i)$ is a scaling function for energy consumption of computation, which is a decreasing differentiable function of the reduction rate δ_i and captures the influence of the reduction rate δ_i on e_{iC}. Furthermore, $y_r\delta_r$ shows the QoI requirement, which is the total amount of data that end-user expects to receive from the area of interest.

Using (3) to (7), the GO problem (1) is a non-convex optimization problem. Even though the GO problem satisfies the sufficient condition for the strong duality gap in [7], the complexity and interdependency among nodes have prevented us from deriving a distributed algorithm for optimal reduction rates. However, we prove in the following that under some conditions, it is possible to reduced the complexity of the GO problem (1) very significantly (i.e., the tree of N nodes to one with $log_2 N + 1$ nodes) such that each node is required to solve the reduced version of the problem. This forms the basis of our proposed distributed approach for the optimal solution for the GO problem. Toward this end, we introduce the following Lemma and Theorem.

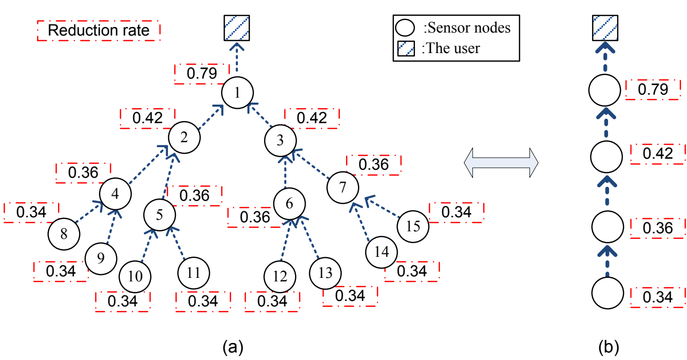

Fig. 1: (a) Reduction rate values for each node in a symmetric aggregation tree. (b) Network topology after complexity reduction.

Lemma. *Assume a symmetrical aggregation tree where: (1) beside the leaf nodes, each node has the same number of children nodes, (2) every leaf node generates the same amount of data, while all other nodes only process and transfer data, and (3) the network and energy consumption parameters in (3) to (7) are identical for all nodes. Under these assumptions, all the nodes at the same level of the tree (say level* i*) have the identical optimal reduction δ_i as part of the optimal solution for the GO problem.*

Proof. Proved by induction. However, duo to space limitation we omit the proof here. ■

For example, Fig.1 (a) shows the optimal data reduction rate for the GO problem (1) for a binary aggregation tree with uniform parameters in (3) to (7). As expected, the optimal reduction rates for all nodes at the same level of the tree are identical.

The following Theorem shows that under the assumptions made in the Lemma, the optimal solution for the GO problem associated with a symmetric aggregation tree, as in 1 (a), is identical to that for liner graph, shown in 1 (b).

Theorem. *For the symmetrical aggregation tree with* h *levels of nodes and assumptions made in the above Lemma, the optimal reduction rates for the GO problem associated with the tree are identical and can be obtained by solving the following problem of a linear graph with $h + 1$ nodes:*

$$\begin{aligned} \underset{\boldsymbol{\delta}}{min} \quad & Y \sum_{\mathrm{i}=0}^{\mathrm{h}} \Big(\prod_{k=i+1}^{h} \delta_k \Big) \, f_i(\delta_i) \\ s.t. \quad & Y \prod_{j=0}^{h} \delta_j \geq \gamma \end{aligned} \quad , \tag{8}$$

where Y is the total amount of data generated at the leaf nodes. h is the number of nodes levels in the aggregation tree which is equal to $log(N)$ and $\boldsymbol{\delta}$ is a vector of reduction rates associated with each level of the tree.

Proof. Duo to space limitation we omit the proof here. ■

The significance of this proposed solution for the global-optimization problem is explained as follows. In general, the problem of in-network processing is a non-convex optimization problem, for which no exact distributed solution technique has been found. Solving the problem by a centralized method does not scale in terms of algorithm complexity and incurs significant overhead in distributed environments. Under the assumption of identical parameters for all nodes, we have shown here that the optimal data reduction rates for a symmetrical tree of N nodes can be obtained by solving the corresponding problem of a linear graph of $log_2(N) + 1$ nodes. This represents a very significant reduction in complexity such that each node can obtain its optimal reduction rate by solving the much reduced problem locally. This new approach can be viewed as a new distributed technique to the very challenging resource-allocation problem. Future work includes the possible extension of the new technique to non-symmetrical settings and the continuation of our effort in pursuing the exact distributed solutions for the in-network processing problem.

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