Computer Networks 75 (2014) 1–17

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Operational information content sum capacity: From theory to practice ☆

Ertugrul N. Ciftcioglu [a,*], Antonios Michaloliakos [b], Aylin Yener [c], Konstantinos Psounis [b], Thomas F. La Porta [c], Ramesh Govindan [b]

[a] IBM Research, Yorktown Heights, NY 10598, United States
[b] University of Southern California, Los Angeles, CA 90049, United States
[c] Pennsylvania State University, University Park, PA 16802, United States

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 19 June 2014
Accepted 23 August 2014
Available online 4 September 2014

Keywords:
Quality of information
Rate allocation
Network utility maximization

ABSTRACT

This paper considers Quality-of-Information (QoI) aware resource allocation policies for multiuser networks. QoI is a recently introduced composite metric which is impacted by a number of attributes of information communicated from the source(s) to the destination(s), and as such differs from traditional quality-of-service metrics considered to date. The focus of this work is defining the Operational Information Content Sum Capacity (OICC-S) of a network, achieved by the set of information attributes supported that maximize sum quality of the network. This quality is defined as a function of the information attributes provided by the source input, as well as the channel induced attributes that impact the QoI delivered to the destination(s). Optimum rate allocation to maximize the output sum quality of information and achieve OICC-S of the network for various settings is provided, and demonstrated to differ from the solution that provides maximum throughput, making QoI-awareness necessary in resource allocation. Insights arising from the analysis are provided, along with those from practical scenarios.

1. Introduction

Traditional approaches for resource allocation based on Quality of Service (QoS) perform network operations that are agnostic to the application or the information content. Such approaches may prove suboptimal for task-oriented networks where the main goal is sound decision making. Several examples for such tasks involve crowd-sourcing, participatory sensing-type applications, as well as tactical networks. To this end, a new paradigm which emphasizes the quality of information by viewing the network as an information source, and developing methods to satisfy information quality requirements at the end user is necessary.

To characterize information quality, there is growing interest in moving from traditional QoS metrics as throughput, packet delivery ratio, fairness, and delay towards new notions of quality associated with information. This effort includes introducing new attributes which characterize the value of information relevant to the specific application [1,2]. Attributes such as provenance, accuracy, precision, reliability, corroboration, credibility, age/freshness, and timeliness have been used to define the quality of information [1–4]. Event detection applications for QoI are studied in Refs. [1,5]. Recently, there have also been studies which focus on QoI-based scheduling [6–8]. In [9,7], we have optimized delivered QoI for scenarios

☆ This work was presented in part at the 14th International Conference on Information Fusion, FUSION 2011, July 2011.

* Corresponding author.
E-mail addresses: enciftci@us.ibm.com (E.N. Ciftcioglu), michalol@usc.edu (A. Michaloliakos), yener@ee.psu.edu (A. Yener), kpsounis@usc.edu (K. Psounis), tlp@cse.psu.edu (T.F. La Porta), ramesh@usc.edu (R. Govindan).

http://dx.doi.org/10.1016/j.comnet.2014.08.017
1389-1286/

with randomness in either channel conditions or traffic, focusing on a source–destination pair. In [6], we have introduced the concept of operational information content sum capacity and demonstrated initial associated theoretical results for a multisource scenario. In this work, we build on [6] to provide a comprehensive study to address QoI-aware network system optimization from both theoretical and practical aspects.

We consider the following scenario. A network is sent tasks sequentially from an end user, and users with sensing capabilities respond to these tasks. We are interested in the set of information attribute vectors that the network can support. Moreover, we identify which of these vectors of information attributes are most useful in terms of decision making associated with the task through a Quality-of-Information function. We denote the maximum sum QoI achieved by these information attribute vectors supported by the network as the *Operational Information Content Sum Capacity (OICC-S)* of the network. Proposed recently, the notion of *Operational Information Content Capacity* (OICC) is an indicator of the decision making capability that the collection of sources and links, i.e., the network can provide [2]. As such, it differs from, for instance, the Network Utility Maximization (NUM) framework where the traditional utility is a function of the flow rates [10]. While there have been recent efforts to include delay-dependent terms in the NUM framework [11,12], we take the viewpoint of optimizing of QoI metrics such as accuracy by file size adaptation at the sources. Another main difference is that while the NUM framework deals with optimal rate adaptation, we include optimization of the attributes at the source in addition to optimal rate allocation. Although the concept of QoI by itself is associated with information generated by a single source, OICC-S captures the interaction of multiple sources or flows and the physical layer they share. More specifically, we address the problem of sum quality maximization via optimal rate allocation given the application specifications and network constraints.

Among the attributes which can effect QoI and OICC-S, we focus on the effects of source-specific attributes as *accuracy* and *timeliness*.[1] Information attributes as accuracy, precision and completeness are indicators of the initial information content and the success of generating information at the sources. Timeliness, which measures the availability of information relative to the time it is needed, is related with success of network delivery. We choose accuracy and timeliness since these two attributes together capture both source and network dependent factors on quality. Accordingly, the overall OICC-S maximizing optimization framework involves both source- and link-level decisions. These sets of attributes possess a trade-off such that improving source attributes can degrade timeliness for a given network. We consider several models for QoI that depends on these two metrics.

We consider various network scenarios with the objective of maximizing the sum quality of the system, i.e., achieving the OICC-S. The main issue we address is obtaining the balance between source attributes, specifically accuracy, and timeliness for the given network, by rate allocation. QoI is a composite function of these source- and network- based attributes, hence maximization of sum quality calls for new treatment compared with the network-centric NUM framework. We first provide theoretical results for a two-user multiple access channel (MAC). For this scenario, it is well known that max weight scheduling maximizes throughput for this model by operating at one of two corner points for the MAC capacity region [13]. In contrast, here, we demonstrate that arbitrary points on the dominant face of the rate region can be optimal rate points to attain OICC-S. Next, we demonstrate that OICC-S optimizing rate allocation strategies significantly differ from throughput-maximizing rate allocation for a several canonical topologies operating with practical protocols as TDMA and CSMA/CA operating with several widely used commercial applications. We conclude, based on the analysis and the simulations that rather than focusing on maximizing the number of bits in resource allocation, QoI-aware policies are necessary to maximize the decision-making capability of a network. The organization of the paper is as follows. In Section 2, we present the basic model and QoI definitions. Next, in Section 3 we formally define the OICC-S. We provide theoretical results associated with rate allocation and information attribute optimization problems to achieve the OICC-S for different settings in Section 4. Sections 5 and 6 present scenarios with widespread applications and practical network settings. We conclude the paper in Section 7.

2. QoI: Definitions, user and application perspective

QoI is a composite, multi-dimensional metric that captures the trade-offs of several components to characterize the information ultimately delivered to the application. QoI as determined by an application is a function of both intrinsic and contextual metrics. Intrinsic metrics are those that are valued independently of the use of the information. For example, the freshness of information, i.e., its age, is a function of when the information was generated, and once delivered will have the same value regardless of the application using the information. Contextual metrics are a function of the use of the information. For instance, completeness depends on the use of information. If a photo is being used to count people in a room, it is only complete if it contains all the people in the room; if its use is to determine if at least one person is in the room, then it is complete if it shows a fraction of the room that contains one person.

Requested QoI is defined as the QoI requested by a user when issuing a task. Delivered QoI represents the QoI delivered to the user, either by retrieval of information in real-time or by retrieving information from a database.

2.1. QoI functions

QoI functions allow a requestor of information to define the relationships and trade-offs between information

[1] Other attributes such as credibility, provenance and freshness can be integrated in the framework.