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Time-optimized contextual information forwarding in mobile sensor networks

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HIGHLIGHTS

- We study on the scheduling of Context Forwarding (CF) in Mobile Sensor Networks (MSNs).
- We formulate the CF scheduling problem as an optimal stopping time problem.
- We propose an optimal CF policy over MSN.
- The proposed policy exhibits efficient CF in MSN.

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ABSTRACT

We study on the forwarding of quality contextual information in mobile sensor networks (MSNs). Mobile nodes form ad-hoc distributed processing networks that produce accessible and quality-stamped information about the surrounding environment. Due to the dynamic network topology of such networks the context quality indicators seen by the nodes vary over time. A node delays the context forwarding decision until context of better quality is attained. Moreover, nodes have limited resources, thus, they have to balance between energy conservation and quality of context. We propose a time-optimized, distributed decision making model for forwarding context in a MSN based on the theory of optimal stopping. We compare our findings with certain context forwarding schemes found in the literature and pinpoint the advantages of the proposed model.

1. Introduction

1.1. Motivation

A mobile context-aware system (MCAS) is in need of the consumption of quality contextual information (context) [37] disseminated among nodes in a mobile sensor network (MSN). Nodes form ad-hoc distributed processing networks that produce easily accessible and quality-stamped information about the surrounding environment. The objectives for the nodes are to sense, process, and transmit context to other nodes. Since nodes have limited resources, they have to balance between energy conservation and quality of context, while transmitting a quantum information. Nodes are trying to disseminate up-to-date pieces of context, captured by other nodes (sources). Useable stored information is retrieved by a MCAS from the nodes. A MCAS exploits up-to-date disseminated context in order to provide enhanced services such as environmental monitoring, security surveillance, military operations, undersea explorations, contextual and situational inference and reasoning [26,31,3].

We consider a MSN involving (a) source nodes (sources), equipped with sensors that generate (sense) and forward context (e.g., luminance, humidity, temperature), and (b) consumer nodes (consumers), that receive, store, and forward context to their neighbours. The consumers attempt to disseminate context of high quality as much as possible while being energy efficient; i.e., keeping the communication load in low levels. This motivated us to introduce an optimally scheduled, quality-aware context forwarding model for the consumers. The proposed model schedules the context forwarding decision (CFD) within a finite time horizon by reducing data transmission and overhead (possible context replication) in light of context quality.

Context quality refers to the utility entailed to a MCAS by the consumption and use of the circulated context in the MSN. We establish context quality through an ageing framework which deprecates context, thus, leading from high to low quality. Freshness is a typical indicator of the quality of context. Consider two pieces of context p and q and a relation $p \succ q$, which denotes that p is *better* than q. The interpretation of the relation $\succ$ associates with the quality indicator of context [27]. Specifically, better context p can be for instance, 'more fresh'; i.e., more up-to-date sensed values, or 'more reliable'; i.e., sensed values captured by reliable/trustworthy

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sources, or 'more specific'; i.e., more detailed[1] context [2], than q referring to the perspective of interest of the MCAS [8]. Each node compares received p with the locally stored q. If $p \succ q$ then the node accepts p, otherwise, the node does not replace q with p. Each node can, further, locally refine information independently of other nodes. It is also possible for a node to exploit the received p in order to generate more valuable information and, thus, forward it across the MSN [8]. We assume:

- a MSN, which consists of mobile nodes (sources and consumers). All nodes adopt the same mobility model;
- consumers receive, store, and forward context to their current neighbours;
- consumers are delay tolerant in the sense that context forwarding can be postponed in search for context with highest quality;
- each consumer assumes a finite time horizon for the CFD;
- the quality of context turns obsolete with time.

A consumer specifies a finite time horizon N in which it makes a decision (CFD) to forward the local context p to its neighbours. **Local context** refers to as the locally stored contextual information in the consumer's cache. The consumer should forward p before the horizon N is reached taking into consideration the rate at which p turns obsolete. The context p at time t has a certain quality value, say f_t. The f_t function has certain characteristics to be discussed in subsequent sections. The consumer, at time t, can forward p immediately to its neighbours. However, the consumer could refrain from forwarding p instantly to its neighbours in order to receive better context q than p, possibly, from another consumer or source from its neighbours at a later time. The consumer could also continue receiving pieces of context of possibly *better f* values until the horizon N. It is uncertain whether better context will be received within N. The horizon N relates to the tolerance capability of the consumer to forward context of best quality. A high N value might result to reception of better context but, also, might result to forwarding of nearly obsolete context since no better context was attained. The consumer delays the CFD through the reception of context with as high quality value as possible (relative to those values seen previously) and, then, forwards it to its neighbours. We formulate this *scheduling problem* using optimal stopping theory [30] and analyse the problem using backward induction [10] since the finite horizon constraint cannot be neglected.

1.2. Motivating examples

Quality-aware CFD results to exchange of high quality pieces of context, since consumers delay context forwarding in light of receiving context of high quality. A time-optimized CFD mechanism can enhance the forwarding policy of an autonomous mobile node (e.g., robot). Specifically, many research efforts have studied systems emphasizing in autonomous mobile nodes [9] for supporting distributed intelligence in MSN. The higher quality pieces of context a MCAS receives, the more capable becomes of interpreting and inferring (new) knowledge (e.g., from typical sensor data fusion to reasoning about more specific context/situational awareness [3]). Certain MCASs based on the exchanged context in a MSN are: 'covering' (explore enemy terrain), 'self-assembling' (reconfigurable robots) [1], 'localization' and 'coverage' (improvement of positioning accuracy; location of land mines) [15]. We can distinguish motivating scenarios in which multiple airborne nodes (unmanned aerial vehicles—UAVs) identify as much quality information regarding a phenomenon as possible, thus, enriching their knowledge on the surroundings, and hover in formation over a ground target. Ground nodes (unmanned ground vehicles—UGVs) collect spatial disseminated information of high accuracy (high spatial resolution) for applying obstacle-avoidance and formation algorithms to navigate an entire flock of robots to the goal. Furthermore, UGVs enter a building, collect specific up-to-date/fresh contextual information and send back high quality visual images of the interior.

Quality-aware CFD can enhance the context discovery process in [4]. In context discovery [4], consumers collaboratively explore, locate, and track sources that generate context. All consumers cooperatively pursue the acquisition of context of high quality by locating sources in a MSN. Evidently, consumers improve the quality of the discovered context through time-optimized CFD, thus, being capable of providing high quality information for the exploration area leading to reliable real-time inferred situations. In addition, quality-aware CFD can be adopted for keeping the communication load in MSN in low levels. For instance, a consumer can delay in delivering aggregated information to a MCAS in light of accumulating more pieces of information from neighbouring nodes. The more information is aggregated the more data accuracy is achieved (e.g., maximum/average value estimation in a data stream). Evidently, aggregation operation eliminates data redundancy and, thus, communication load. In this case, optimality in CFD copes with the trade-off between energy and delay in data aggregation.

Socially-aware networking (SAN) is an emerging paradigm to solve problems of networks consisting of mobile nodes with social properties, e.g. social relationship and mobility patterns. These characteristics can be utilized to design efficient data forwarding/routing protocols in a mobile social network (MSoN). Specifically, a MSoN is a special kind of delay-tolerant network (DTN) in which mobile users move around and communicate/share data with each other via their carried short-range communication devices. Mobile users with common interests autonomously form a *community*, in which the frequently visited location is their common *home*. MSoC can be a mobile vehicular network, a MSN, and a Pocket Switch Network [38]. Recently, certain socially-aware routing algorithms based on SAN have been proposed, e.g., [21,16,40]. For instance, the idea behind the algorithm in [40] is the opportunistic routing of messages in a MSoN through an optimal set of relay nodes for each home, i.e., each home only forwards its message to the node through its optimal set of relay nodes and ignores other relay nodes. In that sense, the discussed algorithm solves the problem of whether a home should select a visited node as the relay node of message delivery or ignore this visited node to wait for those better relay nodes. Quality-aware CFD can be appropriately adopted in SAN especially when dealing with quality-stamped data sharing being optimally routed within a MSoN home.

1.3. Related work

Methods derived from the optimal stopping theory have been applied to information dissemination in ad-hoc networks. The authors in [43] propose an opportunistic scheduling scheme for ad-hoc communications based on the maximal 'rate of return' problem [32]. The model in [43] treats opportunistic scheduling in ad-hoc networks, in which links cooperate to maximize the overall network throughput. The model in [43] focuses on the level of channel probing, whilst our model focuses on the level of forwarding quality context to neighbouring nodes. The data delivery mechanisms in [5,6] deal with the delivery of quality information to context-aware applications in static and mobile ad-hoc networks, respectively, assuming epidemic-based information dissemination schemes. The mechanism in [5] is based on the probabilistic nature of the 'secretary problem' [33] and the optimal online time series

[1] If the MCAS can infer/deduce context q from context p, then context q can be replaced with context p.