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AmI Context-based Cross-Layer Optimization of MAC Performance in WSNs

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Abstract: Direct information exchange between non-adjacent protocol layers or “cross-layer” (CL) interaction can optimize network performances such as energy efficiency and delay. This is particularly important for wireless sensor networks (WSNs) where sensor devices are energy-constrained and deployed for real-time monitoring applications. Existing CL schemes mainly exploit information exchange between physical, medium access control (MAC), and routing layers, with only a handful involving application layer. In this paper, we focus on CL optimization for WSNs in ambient intelligence (AmI) applications, where low-level sensor data on users and their surroundings are collected and processed to infer higher-level user context information for context-adaptive AmI applications. For the first time, a framework for CL optimization based on user context of AmI application and an ontology-based context modeling and reasoning mechanism, is proposed in this paper. We apply the proposed framework to a contention-based MAC protocol for WSNs to adapt its backoff behavior to the user context. Results show that the modified MAC protocol with CL interactions can yield appreciable performance improvement in terms of throughput, frame delay, and energy efficiency.

Keywords: wireless sensor networks; cross-layer optimization; ambient intelligence; context

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1. Introduction

Wireless sensor networks (WSNs) are an enabling technology of smart environments for ambient intelligence (AmI). In AmI, WSNs perform human-centric sensing where low-level sensor data on users and their surroundings are collated and processed to infer higher-level user context information for context-adaptive AmI applications. The high-level user context information is a necessity in AmI applications to deliver personalized services to the users in an intuitive and intelligent way to support their everyday activities. Moreover, we envision such user context information could be harnessed for optimizing the performance of the underlying WSNs through cross-layer (CL) interactions.

By allowing direct information exchange between non-adjacent protocol layers via CL interaction, network performances such as energy efficiency and delay can be optimized [1]. This is particularly important for WSNs where sensor devices are energy-constrained and deployed for real-time monitoring applications. Most research on CL optimization for WSNs have focused on interactions between lower layers of the protocol stack, i.e. physical, medium access control (MAC), and network layers [2]. There was also research on CL optimization that considered application requirements, e.g. quality-of-service (QoS) requirements of multimedia applications [3].

Unlike these previous works that either were not concerned with the application layer or used the application to only define the requirements of CL optimization, this paper focuses on how application derived information, i.e. the user context information derived from AmI application, can optimize the underlying WSN performance through CL interactions.

For the first time, a generic and customizable CL framework that utilizes context information from application layer for optimizing protocol performance in WSNs is proposed in this paper. This framework is sufficiently generic to be customized to different AmI applications. We applied the proposed framework to optimize the transmissions of a contention-based MAC protocol for WSNs by adapting its backoff behavior in real-time to the user context inferred by an AmI application.

The rest of the paper is organized as follows. Section 2 describes the proposed framework. Section 3 outlines the optimized contention-based MAC protocol. Section 4 presents and discusses the evaluation results. Finally, Section 5 concludes the paper.

2. AmI Context-based CL Optimization Framework

In this paper, AmI refers to a human-centric context aware system by which the raw sensor data required to infer high-level user context information are collected and delivered by the underlying sensing and communication infrastructures of WSNs. Optimization of a protocol can be achieved by allowing such inferred context information to become available to the sensor nodes through a context exchange mechanism, and allowing each node to control its transmission of any outbound data based on the data content and inferred context of its surroundings. The framework can be implemented in firmware, and each node in the network runs an instance of the implementation.

2.1. Architecture

This section presents the architecture of the framework, including the functionality and behavior of its constituent components. There are three parts to this framework: i) communication mechanism for network-wide AmI context exchange; ii) node architecture for node-level context handling and CL optimization; and iii) ontology-based context modeling and reasoning mechanism for representing and inferring context within this framework.

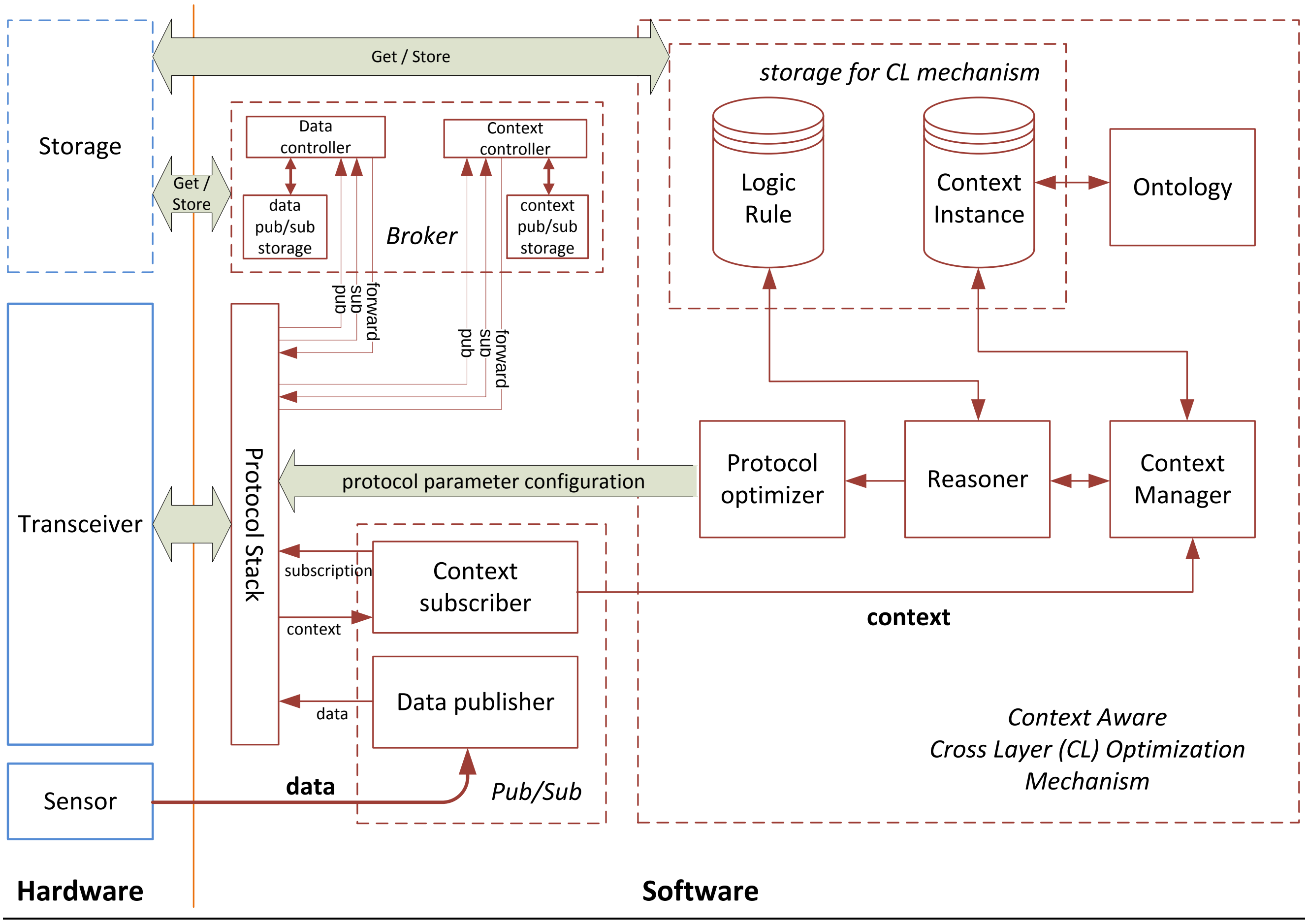
2.1.1. Communication mechanism

The communication mechanism is based on the data-centric publish/subscribe (pub/sub) paradigm [4]. Under this mechanism, AmI is a *publisher* that may publish inferred contexts, while sensor nodes are *subscribers* that may subscribe to published contexts. A virtual broker (VB) is a virtual brokerage entity formed by a cooperative group of sensor nodes that share the responsibility of providing context storage and retrieval services. Hence, any AmI context can be disseminated to subscribing sensor nodes for making informed optimization decisions based on situations of their monitored environment.

2.1.2. Node architecture

Fig. 1 presents the node architecture that illustrates the functionality of node-level context handling and protocol adaptation for CL optimization. This architecture has three hardware components, namely sensor element, transceiver, and storage device, and three software modules, namely Pub/Sub control, broker management, and context-aware CL optimization.

Figure 1. Node architecture



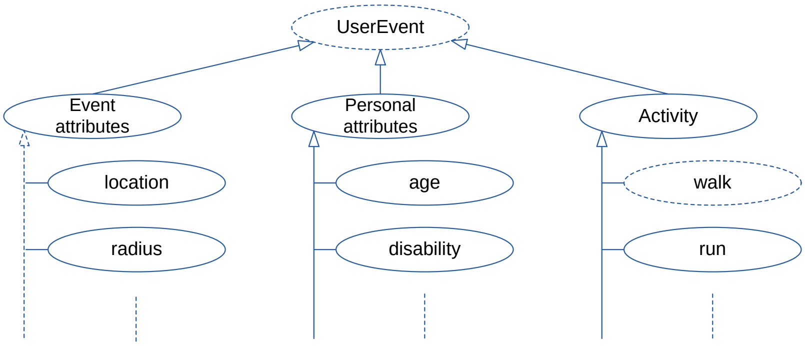
The Pub/Sub control module can allow a sensor node to perform the roles of both a publisher and a subscriber, i.e. not only can the sensor node publish its sensed data to the VB (for AmI to subscribe and generate higher-level user contexts), it can also subscribe to receive the high-level user contexts from the VB (published by AmI and stored on the VB). This creates a bi-directional flow of sensed data (from sensor node to VB) and user context (from VB to sensor node) within the same network. The broker management module is only used when the sensor node becomes a VB member node. It enables the sensor node to perform brokerage functions such as storing received published data and subscriptions, and forwarding matched published data to subscribers.

The context-aware CL optimization mechanism is the key constituent of this framework. Through context subscription, a sensor node can receive AmI context information, which is stored and later retrieved by the Context Manager for processing. The context information is modeled by an ontology. With some logic rules and a logical reasoning component, a sensor node can interpret the context and configure the protocol parameters for the desired performance.

2.1.3. Ontology-based context modeling

Representing context information requires a modeling method to standardize and formalize information, through which a common understanding of the exchanged (global) AmI context by all sensor nodes can be achieved. In this paper, the representation of common AmI context such as user location and activity is shown in Fig. 2, which is based on an ontology-based model derived from our previous work [5].

Figure 2. Context ontology model



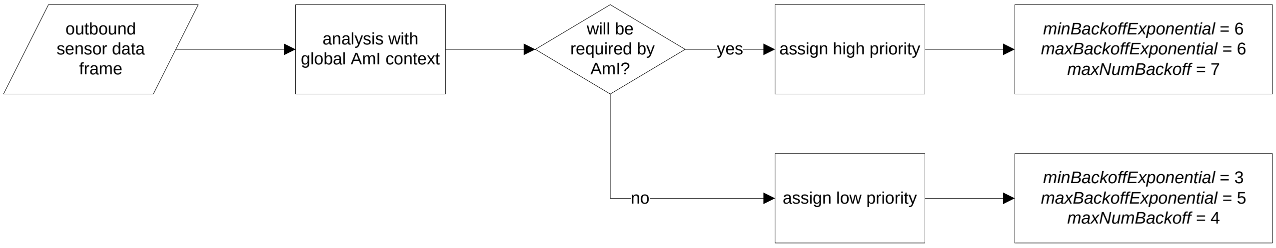
3. A Context-Aware MAC protocol with CL interaction

AmI requires sensor data for context inference. The importance for a piece of sensor data, i.e. its usefulness to the current context inference process, can only be known by AmI. However, if sensor nodes can similarly know about the importance of any sensor data at any given time through context exchange, the WSN may be optimized based on such knowledge. More specifically, situations such as the sensor data published to the VBs does not match with any data subscriptions from AmI while the sensor data required is delayed or lost in the network due to congestion, can be avoided.

The key idea behind this context-aware CL optimization approach is to prioritize WSN communications in AmI according to context information. Therefore, a sensor node that anticipates its data type to become important for AmI’s current context inference process can assign its next data to be published with high priority, and reconfigure its protocol parameters accordingly.

In this paper, a contention-based MAC protocol named Dynamic Reconfiguration MAC (DR-MAC) [6], has been modified to incorporate the proposed CL optimization framework. The original DR-MAC allows three state settings to control the number of backoffs and backoff exponential according to frame loss rate and latency. To incorporate AmI context information, DR-MAC is modified as shown in Fig. 3. The modified DR-MAC is referred to as context-aware DR-MAC.

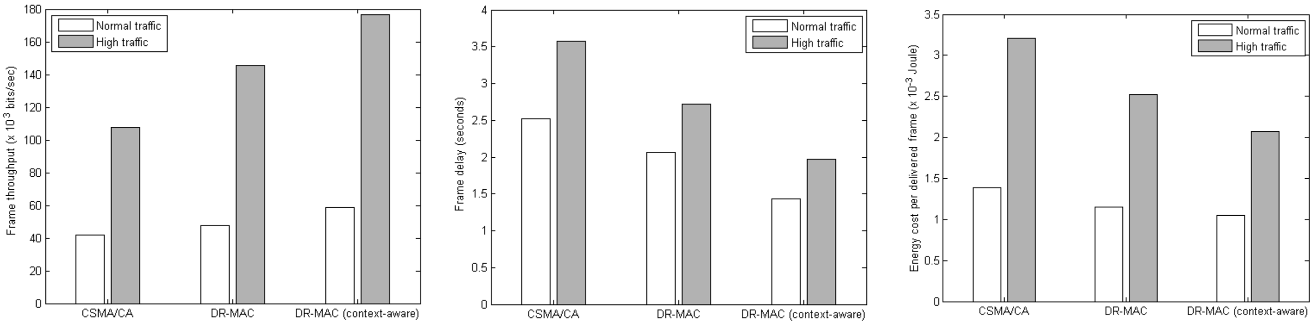
Figure 3. Context-aware DR-MAC



4. Results and Discussion

This section evaluates the performance of three MAC protocols, DR-MAC, context-aware DR-MAC, and IEEE 802.15.4 unslotted CSMA/CA. A WSN with 100 nodes distributed in a 10×10 grid topology over an area of 200×200 m^2 is simulated in OPNET. Each node has a transmission range of 20 m. A VB is formed in the center of network with 4 nodes. 25 non-VB member nodes are randomly selected to become AmI context publishers. The AmI context includes *event attributes*, *personal attributes*, and *activity* (Fig. 2) and their contents are randomly generated during the simulation. 6 sensor data types are defined, along with 5 activities each requiring up to 3 sensor data types to be inferred. This context structure may describe a context such as '*a blind* (personalDisability) *elderly* (personalAge) *is walking* (activity) *across Queens street* (eventLocation) *traffic junction area* (eventRadius)'. Each AmI context publisher subscribes to sensor data types needed to generate its context, which is then published at the rate of 1 frame for every 5 seconds with a frame size of 512 bits. The remaining are ordinary nodes that publish their sensor data to, and subscribe to receive AmI context from, the VB periodically. Two scenarios are specified for publishing sensor data: 512 bits per frame at 2 frames per second for a normal traffic scenario, or 1024 bits per frame at 10 frames per second for a high traffic scenario. Data rate is set to 250 kbps at 2.4 GHz. The current drawn in radio transmit and receive mode is set to 17.4 mA at 0 dBm, and 19.7 mA, respectively, based on

Figure 4.(a) frame throughput (b) frame delay (c) energy cost for a successful frame delivery



(a) (b) (c)

MICAz's specification [7]. For nodes not directly communicating with VB, the AODV protocol is used for multi-hop communication. All results are the average of 10 runs over 180 seconds.

Fig. 4 shows the performance of the three MAC protocols in terms of their throughput, frame delay, and energy cost per successful frame delivery. It is observed that context-aware DR-MAC outperforms the original DR-MAC and CSMA/CA in all three aspects. Under high traffic scenario, the context-aware DR-MAC can achieve up to 22%, 28%, and 18%, improvement in throughput, delay, and energy cost, respectively, over the original DR-MAC. In comparison with CSMA/CA, the improvement is 64%, 45%, and 35%, respectively.

5. Conclusions

This paper proposes a CL framework for protocol optimization in WSNs based on AmI context information. With this framework, a sensor node can receive, interpret, and react to high-level AmI context by suitably reconfiguring its communication parameters. The framework is applied to incorporate a MAC protocol for WSNs with context awareness and CL interaction. This enables a sensor node to anticipate whether its data type have become important for AmI's current context inference process, and accordingly prioritize its outbound data and reconfigure its MAC parameters.

Conflicts of Interest

The authors declare no conflict of interest.

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