QoS-Aware In-Network Processing for Mission-Critical Wireless Cyber-Physical Systems

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Abstract

As wireless cyber-physical systems(WCPS) are increasingly being deployed in mission-critical applications, it becomes imperative that we consider application QoS requirements in in-network processing(INP). In this dissertation study, we are exploring the potential of two INP methods, packet packing and random network coding, on improving network performance while satisfying application QoS requirements. We found that not only can these two techniques increase the energy efficiency, reliability, and throughput of WCPS while satisfying QoS requirements of applications in a relatively static environment, but also can provide low cost proactive protection against transient node/link failures in a more dynamic wireless environment. We are hoping that our solution will provide deep insights on QoS-aware INP protocol design in real-time, mission-critical WCPS.

Keywords

in-network processing, network coding, packet packing, sensor networks, cyber-physical systems

1 Introduction

After the past decade of active research and field trials, wireless sensor networks(WSN) have started penetrating into many areas of science, engineering, and our daily life. They are also envisioned to be an integral part of cyber-physical systems such as those for alternative energy, transportation, and healthcare. In supporting mission-critical, real-time, closed loop sensing and control, wireless cyber-physical systems(WCPS) represent a significant departure from traditional WSN which usually focus on open-loop sensing, and it is critical to ensure messaging quality (e.g., timeliness of data delivery) in CPS sensor networks. The stringent application requirements in CPS make it necessary to rethink about WSN design, and one such problem is in-network processing.

For traditional resource constrained WSN, in-network processing (INP) improves energy efficiency and data delivery performance by reducing network traffic load and thus channel contention. In this study, we focus on two widely used INP methods, packet packing and random network coding, on mission-critical WCPS. Our preliminary results show that these two techniques can significantly improve network performance in terms of energy efficiency, delivery reliability and network throughput under stringent application QoS requirements in WCPS. We are currently exploring how to use these two techniques to provide low cost proactive protection against node/link failures in WCPS.

2 Related Work

In-network processing(INP) has been well studied in sensor networks, and many INP methods have been proposed for query processing and data collection. When controlling spatial and temporal data flow to enhance INP, however, these methods did not consider application requirements on QoS. As sensor networks are increasingly being deployed in mission-critical WCPS, it becomes important to address the impact of QoS requirements on general INP methods, which opens interesting avenues for further research. We focus on two widely used INP methods, packet packing and network coding, in our dissertation study.

2.1 Packet packing

As a special INP method, packet packing has also been studied for sensor networks as well as general wireless and wired networks, [6, 11, 9, 7, 12],where mechanisms have been proposed to adjust the degree of packet packing according to network congestion level [5, 6], to address MAC/link issues related to packet packing [11, 9], to enable IP level packet packing [7], and to pack periodic data frames in automotive applications [12]. These works have focused on issues in local, one-hop networks without considering requirements on maximum end-to-end packet delivery latency in multi-hop networks. With the exception of [12], these works did not focus on scheduling packet transmissions to improve the degree of packet packing, and they have not studied the impact of finite packet size either. Saket et al. [12] studied packet packing in single-hop controller-area-networks (CAN) with finite packet size.

Most closely related to our work on packet packing is [2] where the authors studied the issue of optimizing INP under the constraint of end-to-end data delivery latency. But this study did not consider aggregation constraints and instead assumed *total aggregation* where any arbitrary number of information elements can be aggregated into one single packet. This study did not evaluate the impact of joint optimization on data delivery performance either.

2.2 Network coding

Network coding was first proposed by the very pioneering paper[1] at the beginning of this century to increase the throughput in wired networks. Later this technique was proved to be able to increase network throughput in wireless environment as well. Chachulski et al first studied the combination of opportunistic routing and random network coding in wireless mesh networks[3]. Since then, there have been lots of work done to further improve the throughput of NC-based OR[10][8][4]. The basic idea of these studies is the natural combination of opportunistic routing and network coding because they both made use of the broadcast nature of wireless transmission. [3] proposed the MORE protocol. It used offline ETX metric to coordinate the transmission priority of different intermediate nodes in unicast and multicast traffic. To further improve the throughput of wireless networks, [10] made use of hop-by-hop ACK and sliding window to allow different segments of packets to be transmitted in the network concurrently(CodeOR). To be adaptive to the dynamic of wireless links, [8] used a Cumulative Coded ACK(CCACK) scheme to allow nodes to notifying their upstream nodes that they have received enough coded packets in a simple and low overhead way. The throughput of CCACK is shown to be 45% better than MORE. [4] proposed Rateless Deluge, the first implementation of NC-based OR on sensor networks.

There have also been some works on how to provide protection to networks using network coding. These works used XOR-based network coding to provide reactive or proactive protection in certain fixed topologies, which means we need to build the network topology following certain characteristics. This approach is hard to be applied to WCPS where status of nodes/links is dynamic and ad hoc.

3 Road map

To fully explore the potentials of in-network processing methods in mission-critical WCPS, we started from studying the joint optimization between packet packing, one of the most important QoS requirement in WCPS, and real-time constraint. By understanding the computation complexity of this joint optimization problem under different constraints, we designed a distributed, online protocol *tPack*.

tPack is a transport layer protocol that controls the temporal data flow in a relatively static topology. However, topology is more dynamic in WCPS for some application scenarios, e.g., disaster monitoring and vehicle to vehicle communication. Therefore, to control the spatial data flow is even more important. To provide reliable transmission against single node/link failures in WCPS, we are currently working on developing an opportunistic routing protocol using intra-flow random network coding to provide proactive protection. We found that existing works on NC-based opportunistic routing is not always as energy efficient as single path routing. We designed some algorithms that allow us to build low cost opportunistic routing with network coding and are working on to extend these results into proactive protection of single data flow.

The final step to finish the dissertation includes studying two interesting problems. 1)Explore the use of network coding in more generalized network failure model, e.g. wireless jamming. Different from single node/link failure, wireless jamming can block the transmission in a certain region of the network. 2)Study the potential benefits of applying packet packing and inter-flow random network coding together such that we can control both temporal and spatial data flow. Understanding these two problems can help us design in-network processing protocols that can deliver packets with low cost against different failure models while satisfying application QoS requirements.

In next few subsections, we summarize our current results on each part of the whole study and propose the future research plan.

3.1 *tPack*: a real-time packet packing protocol

In the work of the joint optimization between packet packing and real-time delivery of data, we studied the following problem:

Problem P: Given a collection tree T and a set of information elements $X = \{x\}$ generated in the tree, schedule the transmission of each element in X to minimize the total number of packet transmissions required for delivering X to the sink R while ensuring that each element be delivered to R before its deadline.

We proved that problem **P** is strong NP-hard and there is no polynomial-time approximation scheme (PTAS). This conclusion holds whether or not the routing structure is a tree or a linear chain, and whether or not the information elements are of equal length.

Based on the understanding of the complexity of this problem, we design a distributed, online protocol *tPack* that schedules packet transmissions to maximize the local utility of packet packing at each node while taking into account the aggregation constraint imposed by the maximum packet size. Using a testbed of 130 TelosB motes, we experimentally evaluate the properties of tPack. We find that jointly optimizing data delivery timeliness and packet packing and considering real-world aggregation constraints significantly improve network performance (e.g. in terms of high reliability, high energy efficiency, and low delay jitter). Details and experiment results of *tPack* can be found in [13] and [14].

3.2 Proactive protection for single data flow using random network coding

To control the spatial data flow in WCPS under location-critical and dynamic environments, we make use of the broadcast property and the randomness property of NC-based opportunistic routing to provide proactive protection in WCPS against node/link failures. We are currently studying the following problem:

Problem Q Given a directed acyclic graph(DAG) $G = (V,E)$ with one source S and one destination T, find two node-disjoint sub-DAGs to deliver K packets from the source S to destination T in each sub-DAG using NC-based opportunistic routing with minimal total transmission cost.

The solution to problem **Q** can provide 1+1 proactive protection in wireless networks against single node/link failures. To find the solution to this problem, we first need to find answers to the following problems:

Problem $\mathbf{Q_0}$ Given a directed acyclic graph(DAG) $G = (V,E)$ with one source S and one destination T, find the minimal transmission cost and the corresponding topology to deliver K packets from the source S to destination T using NC-based opportunistic routing.

Problem $\mathbf{Q_1}$ Given a diamond topology $S \rightarrow \{A_1, A_2, \ldots, A_M\} \rightarrow T$, find the minimal transmission cost and the corresponding topology to deliver K packets from the source S to destination T using NC-based opportunistic routing.

We first designed a global polynomial algorithm to give the optimal solution to $\mathbf{Q_1}$. Based on this algorithm, we then designed a global polynomial algorithm to optimally solve $\mathbf{Q_0}$ and another global heuristic polynomial algorithm for **Q**. Due to the constraint of space, details of these algorithms are omitted. The basic idea behind these algorithms is to assign different traffic load to nodes within the same forwarder candidate set based on their transmission cost to the destination. The lower the cost to the destination, the higher proportion of traffic load a node will get. This approach inherits the merit of NC-based OR in eliminating coordination cost between nodes within the same forwarder candidate set, and the advantage of low transmission cost of non-coded opportunistic routing. We are currently studying the asymptotic bound of the algorithm we proposed for **Q** and implementing distributed version of these three algorithms.

3.3 Proactive protection for more generalized failure model using in-network processing

Based on the solutions we proposed in previous works, we will next focus on either applying in-network processing methods in proactive protecting multiple data flows in WCPS for more generalized failure models, e.g. wireless jamming. We will choose to use both packet packing and network coding or only random network coding depending on the potential benefits they can bring to the wireless networks. Using these techniques to control both temporal and spatial data flow, our ultimate goal is to design a cross-layer in-network processing protocol that delivers packets with low cost against different network failure models while satisfying QoS requirements of applications in WCPS. This work will be conducted after the experiment of proactive protection for single data flow using random network coding. And it will complete the dissertation study of INP methods in mission-critical wireless cyber-physical systems.

4 Conclusion

In this dissertation research, we focus on applying in-network processing methods in real-time, mission-critical WCPS to improve network performance from the system perspective and guarantee application QoS requirements from users' perspective. To achieve this objective, We studied how to control temporal data flow using packet packing, and are working on using network coding to control spatial data flow against dynamics in wireless environment, i.e. node/link failures. In the end, two INP methods will be applied together to provide reliable, energy-efficient and real-time performance in mission-critical WCPS. The estimated dissertation time for the student will be in June 2013.

5 Student's biography

Qiao Xiang is a PhD candidate in the Department of Computer Science at Wayne State University in Detroit, Michigan. His research interests include QoS-aware protocol design in wireless cyber-physical systems, scalable multi-core operating systems design and game theory in distributed systems. He started his PhD study at Wayne State University in fall 2007. Since then he has been working in the Dependable Networking and Computing group under the supervision of his advisor, Dr. Hongwei Zhang. He worked as a research intern in the Computer System Research group at Samsung Information Systems America(SISA) during summer 2012. He received his Bachelor of Engineering major in Information Security and Bachelor of Economics from Nankai University in Tianjin, China, in 2007.

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