QoS-Assured In-Network Processing in Wireless Cyber-Physical Systems: A Survey

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Abstract— **Cyber-physical systems (CPS) are expected to transform how people interact with and manipulate the physical world and thus have far-reaching impact on science and engineering. In many CPS such as next-generation vehicle networks, communication via wireless sensor and actuator networks is not only the approach to send or collect data, but also the basis of the adaptive control in the whole system. These systems are called wireless cyber-physical systems (WCPS). Different from traditional wireless sensor networks (WSN) and wireless networks, WCPS emphasize the use of system output as feedback to control system behaviors, which implies that Quality of Services (QoS) has great impact on the design of WCPS. Over the past decades In-Network Processing (INP) protocols in WSN and wireless networks have been extensively studied in order to minimize the energy consumption of nodes. In WCPS, INP will continue to play an important role in communication protocol design due to its advantages. Nonetheless, there has not been a deep study on how to provide different QoS guarantees to users under different INP techniques in WCPS, e.g., real-time and reliability guarantee. This paper comprehensively surveys on current research about different INP protocols and the QoS control in INP protocols. Some open issues are also discussed in this paper. The goal of this paper is not only to introduce different INP protocols and QoS control in INP, but also to provide guidelines for future studies on the joint optimization of INP and QoS in WCPS.**

Index Terms— **Wireless Cyber-Physical Systems, In-Network Processing, Quality of Service.**

I. INTRODUCTION

During the past decade, wireless sensor networks (WSN) have been widely used in many applications, including environment monitoring, homeland security, industry control, and disaster alarm. The community has been doing extensive research on different areas of this field, including embedded system design, communication protocol design, and in-network processing method. Different from traditional computer networks, WSN are highly resource and environment constrained. Each sensor has a limited power capacity, a small memory, and a short transmission range. Due to all these constraints and other application-specific constraints, how to make sensors smartly use their resource, especially their energy, becomes a key challenge for research in WSN. To solve this challenge, different In-Network Processing (INP) methods have been proposed to improve energy efficiency and data delivery performance by reducing network traffic load and thus channel contention. Over the past years, many INP protocols have been proposed for query processing [43][55][42][9] and data-collection [57][39][29][16][17].

Recently, the concept of cyber-physical systems (CPS) is proposed where computation and communication are tightly coupled with physical processes [30]. Many CPS use wireless communication as the basis of sensing and controlling, and we call these CPS wireless cyber-physical systems (WCPS). As a more general family of wireless systems, WCPS focus more on closed loop feedback control of the system, which is different from WSN that mainly consider open loop sensing. Although many existing applications and protocols in WSN can also be transplanted to WCPS, WCPS emphasize more on the quality of services (QoS) of the whole system to support mission-critical and real-time applications.

However, most existing work on INP mainly focus on the optimization of resources without taking Quality of Services (QoS) into account. Most research on QoS in WSN are about QoS-routing or MAC protocol design. Though QoS-assured INP wireless sensor networks has drawn the attention of the community [3][45][56], how to jointly optimize INP protocol design with general QoS constraints is still a largely unexplored area. Because resource efficiency and providing guaranteed QoS are both of great importance to WCPS, studying the joint optimization of these two areas is an urgent task for the community.

In this paper, a comprehensive survey on In-Network Processing protocols and QoS-aware INP is presented. We categorize INP protocols into five classes: data aggregation, packet packing, network coding, data fusion and query processing. We review existing representative protocols in each class. Then we review existing works on providing QoS for INP in WCPS. In the end, some open issues on this area are discussed.

The rest of the paper is organized as follows:, in Section II, some existing INP protocols are described based on different INP methods. Then current works on QoS-assured INP for WCPS are investigated based on different QoS metrics in Section III. Some open issues are further discussed in Section IV. We summarize the whole paper in Section V.

II. IN-NETWORK PROCESSING METHODS

In this section, we categorize INP protocols into five classes: data aggregation, packet packing, data fusion, and query processing network coding. Since there have been a large number of literatures on INP, we mainly introduce the most representative INP methods in each category.

A. Data Aggregation

Data aggregation is the most common INP method in multi-hop WSNs. Data aggregation is defined as the process of aggregating the data from multiple sensors to decrease transmission and data redundancy to the base station, so that the resource of each sensor can be efficiently used [46]. There are tons of literatures on data aggregation so that this survey cannot cover all these works. However, we can categorize data aggregation protocols according to their designing goals.

Most of the early data aggregation research place energy efficiency as their main concern. Different protocols are designed for different network architectures. Chandrakasan *et al.* [7] firstly propose a Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol for cluster-based WSN. The whole network is divided into several small clusters, each of which has a node functioning as a cluster head. Data within a cluster is collected by nodes in the cluster and transmitted to the head node. After all the data is collected by the head node, the head node aggregates all the data and sends the aggregated data to the sink. Nodes in the same cluster take turns to work as a cluster head. Although LEACH improves energy efficiency of the whole network, it has some strong assumptions that limit its development to real world applications. LEACH assumes each node has the same power level and collects data all at a fixed frequency but in real world applications, sensors' energy level may vary and the data collection frequency is arbitrary. Some other cluster-based data aggregation protocols have been proposed to overcome these drawbacks, such as [20][58][2]. However, all these protocols are designed for the case when there is only one hop from the cluster head to the sink. From this point of view, cluster-based data aggregation protocols are similar with data fusion protocols. Differences between data aggregation and data fusion will be discussed in Section II-D.

Besides cluster-based data aggregation, chain-based data aggregation protocols are also studied. A chain-based aggregation protocol called Power-Efficient DATA-gathering Protocol for Sensor Information Systems (PEGASIS)is proposed in [38]. PEGASIS has each node only communicate with its closet neighbor during the transmission to the base station, which means the data is aggregated hop-by-hop. Two modified versions of PEGASIS are also proposed in [38] and both of them try to combine the idea of clustering with chain-based data aggregation. According to the simulation results, PEGASIS can achieve 100% to 200% better energy efficiency than LEACH. Nevertheless, both PEGASIS and its modified versions assume that each node has a global knowledge of all nodes in the network. And the delay to transmit data from the end of the chain to the sink may be very large, especially when the network size is large, even though the authors adopt CDMA technique to allow simultaneous transmissions.

Both cluster-based and chain-based data aggregation protocols organize the aggregation structure into a special tree, i.e., a cluster tree or a chain. Therefore, designing data aggregation tree in WSNs becomes s general focus in the data aggregation area. Ding *et al.* [10] design an energy-aware distributed heuristic (EADAT) algorithm to construct data aggregation tree in WSN. EADAT makes sensors choose their role in the whole tree based on their residual energy. Tan *et al.* [48] propose another data aggregation tree construction algorithm called power-efficient data gathering and aggregation protocol (PEDAP) based on minimum spanning tree. Though PEDAP achieves a better energy efficiency compared with EADAT, it assumes that each node has the global position knowledge of the whole network, which makes it have a high overhead.

Recently, many other references talk about how to build data aggregation tree with different metrics, such as [40] [16]. Lu *et al.* [40] propose a MAC protocol with data aggregation tree construction. Nodes in the tree take turns to be active and asleep. By doing this, not only can the energy efficiency be improved, but also the channel collision problem is alleviated. Fan *et al.* [16] study the scalability issue in data aggregation protocol design. The authors point out that maintaining the whole data aggregation tree structure in large scale networks is resource- and time-consuming. To make data aggregation protocol scalable, the proposed protocol first constructs several small shortest path trees as data aggregation trees. Then the root node of each small tree dynamically decides how to forward and further aggregate the aggregated data to the sink. In this way, the whole protocol becomes scalable and the energy of nodes can be fully utilized since only several small tree structures need to be recorded and updated.

Another designing metric that is often used when designing data aggregation protocols is the network lifetime. In WSN, there is not a general definition for network lifetime. Currently, the most widely used definition is to define the network lifetime to be the time when the first node/the first fraction of nodes in the network run out of its/their energy. Some works have been done aiming to maximize the network lifetime of WSN with data aggregation [24][11][54].

Kalpakis *et al.* [24] give an approximate algorithm to solve the maximum lifetime data gathering (MLDA) problem. The authors divide time into multiple time units, and build a relaxed network flow model on this problem. Based on this model, data aggregation tree is constructed and updated. To make the whole algorithm scalable, a cluster-based MLDA problem is modeled and solved. The proposed model is compared with PEGASIS [38] using simulation. The result show that the network lifetime is significant prolonged by the proposed protocol.

Xue *et al.* [54] model the problem of maximizing network lifetime in WSN as a multicommodity flow problem, in which a commodity represents the data generated from a sensor node and delivered to the sink. They design an approximate algorithm, which can compute (1-ε)-approximation to the optimal lifetime for any $\varepsilon > 0$. Based on this centralized algorithm, they design a distributed data aggregation algorithm. Simulation results show that the distributed algorithm has a much better performance on both energy efficiency and network lifetime than the minimum energy routing (MinEnergy) algorithm, whose goal is to minimize the energy consumption for each data unit routed through the network.

Summary All these works take energy efficiency or network lifetime as their major concerns. However, QoS metrics in data aggregation have already drawn the interests of the community. Related work will be discussed in Section III.

B. Packet Packing

Different from data aggregation, which aggregates spatial or temporal related packets into a packet while the size of the aggregated packet keeps the same, packet packing technique simply put information elements in packets together regardless of the correlation of packets. The length of the packed packet equals to the header plus the length of all information elements. As a special INP method, packet packing has also been studied for WSN as well as general wireless and wired networks. In this survey, we investigate the following works in both WSN and general wireless networks.

Jain *et al.* [23] study the benefits of packet packing in ad hoc wireless networks under IEEE 802.11b standard. The authors point out that 802.11b networks have a high header overhead, which takes up a lot of bandwidth. They alleviate this high overhead by allowing a small delay on packets during the transmission so that intermediate nodes can pack different small packets into a larger packet before forwarding it to next hop. In their protocol, they pre-configure a *maximum aggregation delay* to keep each packet wait at intermediate nodes for a while so that packets can be packed together. Based on both experiments on a wireless testbed and simulations on NS-2, their protocol can provide a significant improvement on network capacity compared with wireless networks without using packet packing. However, there are some drawbacks on this pre-defined waiting time. The end-to-end latency cannot be guaranteed. Meanwhile, by waiting at a fixed time at each intermediate node, a packet may lose the opportunity to pack more other packets at some certain nodes.

Similar with [23], other works [33][35][41] also study the throughput gains by applying packet packing into MAC protocol design. Li *et al.* [33] propose an adaptive QoS-aware frame concatenation mechanism (AQCM) to control how long a packet should wait at an intermediate node. The AQCM is mainly designed for multimedia applications in multi-rate wireless ad hoc networks. AQCM controls the waiting time of every packet by detecting whether the required flow-rate is satisfied, and whether there is a congestion in local traffic. The simulation results show that AQCM can achieve a desirable performance on multimedia multi-rate wireless ad hoc networks. But only soft QoS can be satisfied using AQCM.

Li *et al.* [35] and Lu *et al.* [41] use packet packing technique to design MAC protocol in Ultrawideband Networks (UWBN) and high-speed wireless local area networks (WLANs) respectively. Both of them adopt an opportunistic scheme to do packet packing. Using this scheme, the end-to-end delay of data flows are to some extent improved. But like [23], packets will still lose opportunity to get further packed.

Kliazovich *et al.* [27] design an IP level packet packing scheme in WLANs. The authors categorize IP layer packets into two groups, with low priority and high priority, respectively. Packets in different groups cannot be packed. By this way, packets with high priority, i.e., small delay constraints, will be packed and transmitted first. This scheme is easily to implemented and both experiment and simulation results show that the throughput can be improved using this grouping scheme compared with no packing scheme, and the delay constraint can be satisfied. Though the scheme is easy and direct, the drawback of this scheme is that not only will packets lose packing opportunity, but also the latency constraint can still be violated if packets in the same group have different latency constraints.

Saket *et al.* [47] study packet packing in single-hop controller-area-networks (CAN) with finite packet size. It gives a heuristic greedy algorithm that packs small packets into a single frame as many as possible. Different from [23][33][35][41], this paper study the impact of finite packet size on packet packing.

Summary All references above study packet packing in one-hop wireless networks without putting hard latency constraints on the network model. However, in most mission critical real-time WCPS, not only are they multi-hop networks, but also there are hard latency constraints. In Section III, we will review work that have been done on real-time packet packing in multi-hop WCPS.

C. Network Coding

Network Coding is first proposed for wired networks [1]. By mixing packets at intermediate nodes during the transmission, the bandwidth can be saved and therefore the throughput of the whole network can be significantly improved. During the past years, network coding has been one of the most popular research topics in computer networks. Different coding schemes are designed, categorized into linear network coding and non-linear network coding. Compared with linear network coding, non-linear network coding has been reported to outperform linear coding in several studies [32][12][31][13]. Especially in [13], it is shown that there are multi-source network coding problems for which non-linear coding has a general better performance on throughput. Nevertheless, according to the analysis from [34], linear network coding can provide a performance close to the best possible throughput while only require a relative low complexity compared with the high complexity of non-linear coding.

Due to the broadcast nature in wireless communication, each intermediate node can receive redundant packets during the transmission in wireless networks. Network coding is one of the best choices to make use of these redundancies. By mixing redundant packets together and forwarding the mixed packet, the throughput of the wireless networks can be further improved. It is shown that linear coding functions can be designed randomly and independently at each node [21][22]. They propose a coding technique called random linear coding (RLC). Since RLC can be easily implemented in a distributed manner and it has a low complexity, it is widely used in wireless networks, including WSNs. Furthermore, opportunistic routing, another technique that makes use of the broadcast property in wireless communication, is proposed in [4] with the protocol ExOR, and has drawn the community's interests. Researchers have done some novel research on the hybrid architecture of network coding and routing, especially opportunistic routing, in wireless networks. In this section, we will introduce some representative work in this area.

Katti *et al.* [26] propose COPE, a new architecture for wireless mesh networks. It is the first network coding that is implemented with the current network stack seamlessly. In the design of COPE, only inter-flow network coding is concerned. That means packets headed to the same next hop or generated by the same source cannot be encoded together under COPE. And COPE adopts an opportunistic coding scheme, which does not delay packets' transmissions for further coding opportunity. According to the theoretical analysis, not only can network coding bring a significant improvement on throughput, but also the MAC layer protocol can also improve the network throughput when it is combined with coding technique. COPE is implemented on a 20-node wireless network testbed. The experiment results show that COPE can increase the throughput of wireless mesh networks without modifying routing or higher layers.

As a continuous research of [4][26], Chachulski *et al.* [6] combine intra-flow RLC and the opportunistic routing protocol in [4] together to develop a new routing protocol called MORE in wireless mesh networks. The contribution of MORE is multi-dimensional. First, it makes use of the broadcast property of wireless communication to improve the network throughput without modifying the existing MAC layer, e.g., 802.11. Secondly, it adopts RLC for intra-flow network coding. RLC has a low complexity and is is easy to implement in a distributed system. Therefore, the network throughput is further improved. Thirdly, both the memory overhead and the header overhead are bounded within a reasonable range. MORE is also evaluated in a 20-node testbed and it outperform ExOR in both unicast and multicast traffic flow with a higher throughput.

Koutsonikolas *et al.* [28] propose another intra-flow network coding architecture called Pacifier. Pacifier builds an efficient multicast tree and extends it to opportunistic overhearing. Then it applies intra-flow RLC technique to ensure the reliability. Both these two steps are similar with MORE. Besides these two components, Pacifier also applies a source rate control module to avoid the congestion in the network. Most importantly, Pacifier solves the ”crying baby” problem by having the source send batches of packets in a round-robin fashion. Not only large scale simulations but also a series of experiments in a 22-node wireless testbed show that Pacifier have a large improvement on average throughput compared with MORE.

From the above discussion, we can find that COPE only allows inter-flow network coding while MORE and Pacifier only allows intra-flow network coding. Zhu *et al.* [63] propose a hybrid coding scheme that does inter-flow coding first and intra-flow coding later. In the proposed scheme, packets are first encoded following the same coding scheme adopted by COPE. Then the encoded packets are divided into different batches. Encoded packets in the same batch are further encoded following the same coding scheme adopted by MORE. During the transmission, the whole system use a multiple-path transmitting scheme to further improve the network throughput. The authors do a theoretical analysis on their proposed coding scheme in a simple wireless network model. Compared with COPE, the hybrid coding scheme has a significant improvement on both throughput and reliability in this network model. However, simulation or experiments are needed to further testify the efficiency of this hybrid scheme.

Summary All these works focus on applying network coding into wireless networks so that the throughput can be improved, which is also the top concern of network coding. However, other QoS metrics of users are ignored in these works. There are other work studying on the trade-off between throughput and other QoS metrics, e.g., delay and reliability. We will leave the review of these works in Section III.

D. Data Fusion

From the previous discussion, we can find that data aggregation, packet packing and network coding are INP methods used to design communication models so that the traffic flow in WSN can be reduced. Different from these three INP methods, data fusion and query processing are INP methods more close to the application layer in WCPS.

Data fusion is a collaborative signal processing technique that is widely used in distributed systems to enable the cooperation among multiple devices with limited sensing capability [51]. This technique has been widely studied for decades. Due to the limited sensing capability, the limited energy capacity, and the application background of WSN, data fusion has a wide application prospect in WSN applications. Though it has a similar definition with data aggregation, data fusion is a more general technique that is more close to the application layer in WSN. In data aggregation, data from different sources are simply aggregated or compressed at some intermediate node so that the whole traffic in the network is reduced. However, in data fusion, not only is data aggregated or compressed, but also it is processed along the transmission to the sink to provide guarantee for data accuracy. Each individual sensor in the whole network can play the role as a decider. In other words, with data fusion technique, WSN can work as a distributed detection and decision making system. Different data fusion architectures and systems are designed to fully use the limited resources in each sensor and in the meantime to guarantee the data accuracy. In the following, several representative works on data fusion in WSN are reviewed while data aggregation cannot provide this function. Same as data aggregation, there are vast literatures on data fusion in WSN. In this section, only some important work are reviewed.

Thomopoulus *et al.* [50] study the optimal data fusion in the sense of the Neyman-Pearson (N-P) test in a centralized fusion center. In the whole system, each sensor independently executes a N-P test and sends the decision result of the test back to the sink instead of sending the raw data. After receiving all decision results, the sink makes a final decision and adjusts the threshold of the whole test based the final decision. This is an early work on data fusion in sensor networks. The whole system is built on sensor networks with powerful sensor, which does not take energy efficiency into account.

Similar to [50], Niu *et al.* [44] propose a distributed detection protocol in WSN. In the proposed protocol, each sensor also individually and independently runs a hypothesis test and only sends the test result back to the sink. The difference between [50] and [44] is that the latter one considers the spatial correlation of data sensed by different sensors. The authors reach the conclusion that if the number of sensors is sufficiently large, the proposed fusion rule can provide a very good system level detection performance, in the absence of the knowledge of local sensors' performances and at low signal to noise ratio (SNR). Though the authors mention that sending only decisions from sensors to the sink could reduce the traffic in the networks, they do not formally take energy efficiency into account, either.

These two work are two early ones on applying data fusion into WSN and they mainly focus on the data accuracy provided by fusing distributed decision value together. The energy efficiency is only a by-product. Clouqueur *et al.* [8] systematically compare the performance of distributed detection systems in WSN using value-based data fusion and decision-based data fusion. In value-based data fusion, raw data is directly sent back to the sink, the sink fuses all raw data, abandons the outliers, and makes the final fusion. In decision-based data fusion, the paper adopts a similar way in [50][44], which sends back only decision calculated by each individual sensor to the sink. The authors conduct simulations to compared the performance of these two fusion schemes with robustness as the main metric. The results show that when the proportion of failed sensors in the whole network increases, decision-based fusion outperform value-based fusion by providing a lower false decision probability, a lower power consumption and a higher packet delivery probability.

Even though Clouqueur *et al.* [8] study the energy efficiency of both value-based and decision-based data fusion in WSN, the authors do not discuss how to further reduce the traffic in WSN by allowing data fusion in sensors. Kumar *et al.* [29] develope an architectural framework, DFuse, for distributed data fusion in WSN. There are two main components in the framework of DFuse. First, a fusion API is implemented so that the system can afford the development of complex sensor fusion applications. Secondly, the authors propose a heuristic algorithm to decide which set of sensors can play the role of fusion center. The idea of fusion center is similar as the cluster head in data aggregation. But not only does the fusion center is aware of the energy efficiency of the whole network, but also it helps distributed fusion operation in the network. The performance of DFuse is evaluated via simulation. The results show that DFuse can make sensor use energy in an efficient way. The simulation also analyzes the latency caused by data fusion, but no bound of latency can be guaranteed in DFuse. Furthermore, although the evaluation studies the impact of different energy cost function on DFuse, it does not talk about the impact of DFuse on different fusion applications.

Duarte *et al.* [14] propose a distance-based decision fusion scheme for the collaborative target detection and classification of moving vehicles using acoustic spectral features. The authors design a new scheme to use the distance between the target and the sensor as a parameter to select sensors that can give a reliable detection result to participate decision fusion. This scheme makes use of an intuition that sensors far from the target will have a lower probability of making correct classification decisions. Therefore, only sensors close to the target can participate the target detection and classification. In this way, the communications within WSN is reduced so that energy efficiency is achieved. Simulation results show that the accuracy of target detection and classification is guaranteed and the energy efficiency is improved. Though data accuracy is guaranteed, the proposed scheme does not take other QoS requirements, e.g., reliability and delay, into account.

Summary All work mentioned above focus on how to apply different data fusion methods into WSN so that the data accuracy is guaranteed. In the meantime, energy efficiency is also improved by using data fusion in WSN. In Section III, we will review some works on how to provide assurance on other QoS metrics, besides data accuracy, to users when using data fusion in WCPS.

E. Query Processing

The previous four INP methods are mainly used for data collection in wireless sensor networks. In data collection applications, data are sent back to the sink periodically or based on some certain events. Although in some applications, this traffic pattern is necessary, this pattern has two drawbacks in some other applications [55]. First, since sensors are preprogrammed before they are set into real environment, users cannot easily change the working mode of the whole network if the traffic pattern is prefixed. Secondly, sensors may use up their energy very quickly if they keep sensing and transmitting data periodically. Therefore, collection data based on a distributed query processing mode is more efficient in some applications, such as environment monitoring and inventory management. In this part, we will discuss several representative architectures of query processing in wireless sensor networks.

To the best of our knowledge, Yao *et al.* [55] is the first paper studying the query processing in wireless sensor networks. The authors start this area by proposing a whole architecture of this query processing scheme called Cougar .The whole system works as follows: after a user issues a query request, a query optimizer in the sink first decides which part of the whole network is needed to answer this query, then the query is optimized so that the traffic load in the sensor network is decreased.

Based on [55], Madden *et al.* [42] present a Tiny AGgregation (TAG) service for query processing in low-power, distributed, wireless environments. TAG operates in a similar way as Cougar: users put query request from a powered, storage-rich base station. Operators that implement the query are distributed into the network by piggybacking on the existing ad hoc networking protocol. Sensors route data back towards the user through a routing tree rooted at the base station. During the transmission process, data is aggregated according to different kinds of query specified in the query. Not only does this paper give a systematic architecture of the whole query processing scheme, but also different aggregation methods are defined for different query types. Simulation results demonstrate the effectiveness and robustness of the whole TAG scheme.

Yoon *et al.* [57] propose a Clustered AGgregation (CAG) algorithm to further improve the energy efficiency of query processing. CAG algorithm divides sensors in a wireless sensor network into clusters, in which nodes are spatial correlated and therefore sense similar values within a given threshold. These clusters remain the same as long as the sensed value of nodes in the same cluster keeps within the given threshold. Different from TAG, which requires data from a whole region of the network, in CAG only cluster head nodes need to send data to the sink since data sensed by the sensors in the same cluster are both spatial correlated and temporal correlated. The experiment results show that, although CAG sacrifices a very small percentage of data accuracy, the whole number of transmissions in CAG is significant less than that in TAG, which makes the whole network more energy efficient.

As a continuous work of [42], Madden *et al.* [43] designe and implement a distributed query processor that runs on each of the nodes in a sensor network, which is called TinyDB. The authors make a simple extensions to SQL for controlling data acquisition, and study the influence of acquisitional issues on query optimization, dissemination, and execution. In TinyDB, a semantic routing tree is designed to help nodes decide whether any of their children needs to participate the response to the query request. After the query is optimized, TinyDB defines different policies for the response of different types of queries to reduce energy consumption and fully use the bandwidth. Experiment results show that TinyDB can provide significant reductions in energy consumption in the query system on wireless sensor networks.

Summary As we can find from the above introduction on different query processing architectures, energy efficiency is the main designing goal of these query processing architectures as well as what data aggregation, data fusion, and packet packing do. Even though all these systems provide some guarantee on data accuracy, how to shorten the response time of query processing systems, which is composed of query dissemination time, in-network data processing time and data transmission time, in wireless sensor networks is still an open issue. In the next section, we will conduct a survey on some preliminary research on QoS-assured INP for WCPS.

III. QOS-ASSURED INP IN WCPS

In the previous section, I did a review for representative works on INP in WSN and general wireless networks. Most of these works focus on how to achieve energy efficiency for the whole network. Some of them, e.g., works on data fusion and network coding, also guarantee the data accuracy or network throughput. However, in mission-critical, real-time WCPS, other QoS metrics other than data accuracy and network throughput are also of great importance, and two types such metrics are reliability and latency. Recently, researchers have started to design INP protocols with hard QoS guarantee in WCPS. In this section, we will investigate the research progress in this field. In mission-critical real-time WCPS, latency and reliability are the most important QoS metrics. Therefore, in this survey, we mainly focus on studies on latency-guaranteed INP and reliability-guaranteed INP.

A. Latency-Guaranteed INP

Even though most INP protocols aimed to achieve energy-efficiency or to prolong the network lifetime, there are some works studying the latency-constrained INP protocol design, which provide significant insight on the systematic research on QoS-awared INP design in WCPS. These work focus on the transmission scheduling issues in WSN or wireless networks.

1) Data Aggregation: Yang *et al.* [60] study the energy-latency trade-off for data gathering in WSN. Although this paper still uses energy efficiency as the objective function, the authors put hard latency constraints on the problem definition. This research assumes that the data aggregation structure has already been built. In each data collection round, each non-root node generates one piece of data and every piece of data should be sent to the base station within its latency constraint. During the transmission, data from different sources can be aggregated so that only aggregated data needs to be transmitted to the sink. The objective is to find a transmission and aggregation scheme for the whole data aggregation tree in each data collection round, such that the total energy consumption is minimized and every data is sent to the sink without violating the latency constraint. The authors give a nonlinear programming model for this problem and solve it using a numerical algorithm. Then a pseudo-polynomial time approximation centralized algorithm based on dynamic programming is designed for this model. Furthermore, the authors implement an on-line distributed algorithm to adaptively control the transmission and aggregation policy of each node. It adopts a feedback control scheme to make nodes transmit faster if there are data violating the latency constraint. The proposed protocol is evaluated in simulation. The results show that the distributed protocol can give a good approximated performance compared with the numerical algorithm and the dynamic programming centralized algorithm in terms of energy consumption. And its adaptivity is also demonstrated. As a starting paper on the energy-latency trade-off in data aggregation, this paper gives a good approximate algorithm to solve the problem modeled in this paper. However, the problem definition is relatively simple since in each instance, only one data s generated at one source in each round. And the proposed distributed algorithm requires the cooperation from MAC layer protocols to minimize the interferences between nodes.

Becchetti *et al.* [3] systematically study the complexity of latency-constrained data aggregation scheduling problem in WSN under different models. Different from [60], this paper studies the complexity of latency-constrained data aggregation scheduling problem on different aggregation structures and different traffic patterns. Instead of minimizing the total energy consumption, the authors define two different objective functions. The first one is to minimize the total expected number of transmissions (ETX) given that each link has a constant ETX regardless of packet size, and the second one is to minimize the maximal total ETX in one node. This paper proves that when the data aggregation structure is a tree, the whole problem is NP-hard for both two objective functions with a reduction from the SAT problem. However, both problems are proved to be 2-approximative. The authors also give a polynomial dynamic programming algorithm to solve the problem with the first objective function in a chain data aggregation structure. Besides, this paper also proposes a simple aggregation algorithm that evenly divides the spare waiting time for aggregation at different intermediate nodes along the transmission path. The authors analyze the competitive ratio of this algorithm and the upper-bound for the competitive ratio of all possible algorithms for this problem on different aggregation structures. This paper gives a complete theoretical analysis on the complexity of latency-constrained data aggregation in WSN, which builds a good theory foundation for the latency-guaranteed data aggregation research. The drawbacks of this paper are that: 1) it does not evaluate the proposed simple packing scheme on either simulation or experiment; 2) the competitive ratio and the bounds have too many parameters, which makes the ratio highly depending on specific data aggregation structures.

As a continue work of [3], Oswald *et al.* [45] propose another approximate algorithm for the latency-constrained data aggregation problem. Instead of using energy efficiency as the objective function, this paper defines the objective function to minimize the transmission cost. The authors define energy cost functions for energy consumption on transmissions and delay cost functions for nodes to hold data for further aggregation opportunity. The transmission cost is defined as the sum of energy cost and the delay cost. The paper proposes an approximate algorithm to solve this problem. They derived a competitive ratio $O(min(h,c))$of this algorithm for tree structure, where h is the tree's height, and c is the transmission cost per edge, and a competitive ratio $\Theta(min(\sqrt{h},c))$ for chain structure. Both these two ratios are proved to be tight since the upper bound of the competitive ratio is proved to be at least $\Omega(min(h,c))$. Similar as [3], this paper only focuses on theoretical analysis and does not give simulation or experiment evaluation for the proposed algorithm. And the importance of this paper is weakened because the objective function is not defined objectively. It would be more appropriate to define the objective function to be minimizing energy consumption.

Latency constrained data aggregation is also studied in Vehicular Ad hoc Networks (VANETs). Yu *et al.* [59] propose a data aggregation protocol called CatchUp for data aggregation in VANETs. CatchUp dynamically controls the data forwarding delay in VANETs so that data can be fully aggregated during the transmission with an allowable delay. Different from data aggregation in WSN, where all data has the same base station as the destination, data aggregation model used in this paper is defined that each vehicle would broadcast its sensed data to every other vehicle in the network. CatchUp defines a rewards function for each node in the network to decide what action to take to have a maximal reward. Similar with [45], the energy efficiency and latency constraint are not directly shown in the problem definition. And CatchUp uses a local heuristic algorithm for each node to make decisions, which can only provide soft local latency guarantee.

Compared with [59], Ye *et al.* [56] gives a more systematical solution on local latency-constrained rewards maximizing algorithm. this paper models the problem on a single node in a WSN using data aggregation. In this paper, the authors build a semi-Markov chain decision making model for each node, the impact of latency constraint of data is defined as a negative-exponential rewards function. With the help of some important characteristics of semi-Markov chain, the paper show that once the statistics of the data arrival and the availability of the channel satisfy certain conditions, there exist optimal control-limit type policies which are easy to implement in practice. In the case when the condition of the existence of optimal transmitting and waiting policy is not satisfied, the paper provided two learning algorithms to solve a finite-state approximation model of the decision problem. Simulation results show that under two data aggregation schemes: fixed degree of aggregation (FIX) scheme and on-demand aggregation (OD) scheme designed in [19], both the optimal transmitting and waiting policy control algorithm and two approximate learning algorithms could effectively reduce the energy consumption while the data delay is guaranteed in a low value. Although it does not pose any hard latency constraint on the semi-Markov chain model, the fast decrease property of negative-exponential rewards function ensures that holding data for a long time for further data aggregation opportunities will not happen in the proposed algorithms.

Summary All work discussed above mainly aim to provide soft latency guarantee in WSN. However, in mission-critical real-time WCPS, hard latency guarantee is one of the most important constraints. The theoretical analysis given in [3] provides people a guideline in hard latency-constrained data aggregation. Other open issues are discussed in Section IV.

2) Packet Packing: In the above section, some work on latency-constrained data-aggregation in WSN are introduced. However, there are not as many literatures on the same problem in packet packing. To the best of our knowledge, only the following two papers are related to this topic.

We discussed [27] in Section II-A. Therefore, I will not repeat the discussion again. The only note that needs emphasis is that, though [27] proposed a simple packing scheme by classifying packets into different priority, the proposed scheme cannot guarantee either energy efficiency or latency constraints.

He *et al.* [19] develop a novel adaptive application-independent data aggregation (AIDA) protocol to provide soft latency guarantee for packet packing in WSN. AIDA is designed to be an independent layer between network layer and MAC layer. Packets can be packed in this layer under different packing schemes. The authors propose three different packing schemes. The first one is called fixed scheme (FIX), where AIDA packs a fixed number of network units into each AIDA payload. To ensure that network units do not wait an indefinite amount of time before being sent, a time-out threshold is pre-defined in the system. The second scheme is called On-Demand Scheme (OD), which adopts an opportunistic packing policy. OD puts the real-time guarantee as the top concern. Packets at the same sensor can only be packed when the MAC layer is not available for transmission. In FIX scheme, the system can only provide a soft latency guarantee and packets will lose opportunities to get further packed. In OD scheme, hard latency constraints is guaranteed but packets have less opportunities to get packed than in FIX, which can increase energy consumption. To balance the energy efficiency and the latency requirement, the authors propose the third scheme called dynamic feedback scheme (DYN). DYN implements a combination of OD scheme and FIX scheme where the number of packets packed in one sensor is adjusted dynamically via a feedback control from the output. In the case of low network traffic, DYN will default to the OD mechanism delivering packets to the MAC transmission queue as soon as they are ready. As network traffic builds up and the contention delays transmission, the feedback loop adjusts the threshold of number of packets that can be packed together to allow a greater degree of packing prior to sending. Simulation results indicate that DYN outperform OD and FIX by providing a lower average end-to-end delay, especially in heavy-load traffic. Nonetheless, the proposed DYN scheme have over-reaction or under-reaction on the change of MAC delay, which cannot provide hard latency guarantee for each single packet.

Summary From the above discussion, we can find that there has not been any study on how to provide hard latency guarantee for packet packing in WSN, which is important in mission-critical real-time WCPS. We will talk about this as one of the open issues in Section IV.

3) Network Coding: The main goal of network coding technique is to improve the network throughput. Therefore, there have not been many literatures talking about the latency-constrained or throughput-latency trade off for network coding in wireless networks and WSN.

Eryilmaz *et al.* [15] is the first work studying the delay performance gains from network coding. The authors study the problem on a wireless network model with one source and multiple receivers. Files are transferred from the source to receivers using network coding. The delay performance in this paper is defined as the average complete time of a file transmission. The authors study two different cases: 1) a file is broadcasted to all receivers (broadcast case); 2) each receiver demands a different file (multiple unicast case). According to the theoretical analysis in this paper,there is a significant delay performance gain in both broadcast case and multiple unicast case via network coding, i.e., the average completion time is reduced.

Even though from the analysis in [15], network coding is proved to be able to provide average latency guarantee, there is still a trade-off between the throughput and end-to-end latency for network coding in different wireless networks. A simple example used in [18] is as follows.

Suppose there are k packets needed to be sent from node A to B, link AB has a reliability of 50%. If node A sends these packets separately, it would require an expected number of transmission $4k$ including sending back k ACK packets. If all these packets are generated by A at the same time and therefore could be coded into k coded packets. Successfully sending these k coded packets would require an ETX of only $2k+1$ including sending back only 1 ACK packet. If $k/2$ packets are generated first and has to be sent to B before the other $k/2$ packets are generated, these k packets could only be coded into two groups with $k/2$ coded packets each. The whole ETX for this transmission scheme is $2k + 2$ including sending back 2 ACK packets.

From this example, we may find that similarly with packet packing, network coding can have different throughput due to latency constraints. By affecting the number of packets that can be coded, latency constraints will have impact of the total ETX, and further have an impact on the throughput. We will introduce the following three references on the throughput-latency trade-off with network coding in wireless networks.

Zhang *et al.* [62] investigate the benefits of using Random Linear Coding (RLC) for unicast communications in a mobile Disruption Tolerant Network (DTN) under epidemic routing. In this paper, the authors propose the following coding and transmitting scheme: DTN nodes store and then forward random linear combinations of packets as they encounter other DTN nodes. The simulation results show that when there is one single file composed of several packets propagating in the network, when bandwidth is constrained, applying intra-flow RLC over packets can improve the delivery delay to deliver the whole file, and there is more improvement when the buffer in each node is limited. When there are multiple files propagating in the network, simulations results show that intra-flow RLC offers only slight improvement over the non-coded scheme when only bandwidth is constrained, but more significant improvement when both bandwidth and buffers are constrained.

The work in the above paragraph studies the benefits of network coding in DTN by a simulation based approach. Different from [62], Lin *et al.* [37] study this problem in a theoretical analysis framework. The theoretical analysis achieves similar conclusions as those in [62]. Based on the analysis, the authors also design a priority coding protocol, in which packets in the same file are divided into different groups with priorities and packets with higher priority would be coded and transmitted first. When the destination receives all coded packets for a certain level, it notifies the whole network and the source so that the same packets stored in the network will be dropped to further increase the performance of the network.

In both [62] and [37], the authors do not consider interferences in the network, which is reasonable only for sparse networks. Zhang *et al.* [61] conduct an analysis on the throughput-delay tradeoffs in mobile ad hoc networks (MANETs) with network coding, and compare results in the situation where only replication and forwarding are allowed in each node. The network model is built on both fast mobility model (i.i.d. mobility model) and slow mobility model (random walk model). The authors propose a k-hop relay scheme in a n -node MANET using RLC in MANETs and prove the trade-off between throughput and delay of the proposed scheme under two mobility models. Under fast mobility model, where $k = \Theta(\log n)$, the throughput $T(n) = \Theta(1/n)$ and the average delay $D(n) = \Theta(\log n)$, where $T(n)$ represents throughput and $D(n)$ represents average delay. Under the slow mobility mode, where $k = \Theta(\sqrt{n})$, $T(n) = \Theta(1/n)$ and $D(n) = \Theta(\sqrt{n})$. This is the first work to study the trade-off between throughput and delay using RLC in MANETs. However, this study still uses the average delay as the metric instead of putting hard latency constraints on the analysis.

Summary From the review of these work, readers can find that hard latency-constrained network-coding is still an unexplored area. We discuss it as one of the open issues in Section IV.

4) Data Fusion: In contrast to data aggregation, packet packing and network coding, real-time performance analysis of WSN designed based on data fusion and query processing has received little attention. As far as we know, there is no literature studying hard latency-constrained query processing schemes, but studies from the field of data aggregation can be used to design query processing architectures in WCPS because data aggregation could provide support for efficient query processing. In terms of real-time data fusion, only the following paper study the real-time performance for data fusion in WSN.

Tan *et al.* [49] develop an analytical framework to study the real-time surveillance performance of large-scale WSN that are designed based on collaborative data fusion schemes. The authors define a delay metric called α-delay that is defined as the delay of detecting an intruder subject to the false alarm rate bound by α. The roadmap of this paper is as follows: compared with intruder detection systems in WSN without data fusion, data-fusion-based systems require a smaller network density to achieve a false alarm rate α. Network density will further affect the end-to-end latency in WSN. Therefore, to achieve minimal α-delay, the ratio of network density of WSN with data fusion scheme and without data fusion scheme has an asymptotic tight bound of $\Theta(\frac{SNR}{Q^{-1}(\alpha)})$, where Q^{-1} is the inverse function of the complementary cumulative distribution function of the standard normal distribution. Simulations with realistic settings show that data fusion can reduce the network density by about 60% compared with the a general disc model without fusion while detecting any intruder within one detection period at a false alarm rate lower than 2% and guaranteeing that the detection delay is minimal.

Summary Study in [49] is a good start to study latency-assured data fusion protocol. Nonetheless, the definition of delay is probabilistic and a more general framework is needed.

B. *Reliability-Guaranteed INP*

Same as latency, reliability is another important QoS measurement required in WCPS, especially in mission-critical real-time systems. Nonetheless, most INP can provide a high data delivery reliability without adding any reliability constraints. An intuitive explanation for this phenomenon is that INP methods could effectively reduce the traffic flow in WCPS, which would correspondingly reduce collision and interferences in the network. Therefore, reliability is further improved due to the improvement of the transmission environment. From the above discussion, it is easy to see that data aggregation, query processing and data fusion protocols have a good performance on reliability since the traffic flow is significantly reduced. Nonetheless, readers may ask the question about the reliability in packet packing protocol and network coding schemes. In this section, we will discuss some INP protocols that can provide a high reliability for packet packing and network coding in WCPS.

We discussed the AIDA protocol designed in [19] for packet packing in WSN. In practice ETX is an exponential function of packet size, packing small packets into a larger one can increase link ETX and therefore affect the reliability. However, in simulations, the authors also study the reliability of AIDA under different packing schemes. The results show that FIX, OD and DYN all have a high reliability compared with no packing scheme. One possible explanation is that although sending larger packets may cause a high ETX, packing schemes in AIDA, especially DYN. can adaptively decide how many small packets can be packed together so that packing can always bring more benefits than the cost of ETX increase.

Similar findings can also be found in [26][6][28]. Reliability can still be guaranteed when network coding is used in WCPS. We take [28] as an example. In the Pacifier protocol proposed in [28], the ”crying babies” problem in multicast is solved by using a round-robin batching scheme. As long as one receiver has received enough packets to decode, the source will not sending packets to this receiver. The theoretical analysis of Pacifier shows that one hundred percent reliability can be achieved. A similar idea can also be found in [36].

To the best of our knowledge, Kamra *et al.* [25] is the first work to put reliability as the major concern for network coding in WSN. The authors propose Growth Codes, a new class of network coding particularly suited to sensor networks where data collection is distributed. Unlike previous coding schemes, Growth Codes employs a dynamically changing codeword degree scheme that delivers data at a much faster rate to network data sinks. Furthermore, the coding algorithm is designed such that the sink is able to decode a substantial number of the received coded packets at any stage. Simulations in TOSSIM and experiments show that Growth Codes provides a high reliability in WSN where nodes are highly prone to failures.

Summary Since reliability is usually implicitly guaranteed in INP protocols, there have not been many work on providing reliability guaranteed in INP. Nonetheless, it is necessary to design a general analysis framework on how much reliability can be provided in different INP since reliability is the top concern in mission-critical WCPS.

IV. OPEN ISSUES

From the previous discussion, we can find that, in resource-constrained wireless networks, in-network processing (INP) effectively enhances messaging efficiency by reducing network traffic load. Nonetheless, the study of INP in wireless and sensor networks has mostly ignored the issue of providing hard quality-of-service (QoS) such as the timeliness of data delivery when controlling the temporal and spatial data flow in networks. Therefore, how to provide QoS guarantee for INP in WCPS is still a new area where only some preliminary works have been done. In this section, we point out some open issues and research challenges in this field. We categorize these challenges into four classes: systematic modeling and complexity analysis, joint optimization of QoS and WCPS-specific INP, combination of different INP methods and theoretical foundations of algorithm.

A. Systematic Modeling and Complexity Analysis

Because QoS constraints are added to INP protocol design for WCPS, the problem formulation will be different from that in existing research on energy-efficient INP design in traditional WSN and wireless networks. In [56][52] authors have proposed some simple modeling frameworks for QoS-aware data aggregation protocol design based on network calculus and semi-Markov chain. Nonetheless, these frameworks are used for specific QoS constraints, such as reliability and latency, and only for data aggregation. And we still lack a general modeling framework across different QoS constraints and different INP methods to push the research on this area. In [53] the authors give an interval graph model for the latency-constrained packet packing problem, which may also apply to general QoS-aware INP scheduling problem in WCPS, But the QoS-aware INP structuring problem still needs a modeling framework.

Besides modeling issues, complexity analysis is also of great importance in this area. Complexity of problems may change due to the joining of new QoS constraints. Some QoS constraints may make the new problem easier, especially in a chain network[53][3], while some constraints may make the new problem even NP-hard to approximate[3]. A complete complexity analysis on QoS-aware INP problem will provide a guideline on how people can design and implement efficient approximate algorithm in WCPS.

B. Joint Optimization of QoS and WCPS-specific INP

From the survey in Section III, readers can find that existing works on QoS-aware INP design mainly consider how to provide service in WCPS with guaranteed latency and reliability. Although in mission-critical real-time WCPS, these two metrics are the most important ones, there are other QoS metrics unexplored, e.g.,interactivity.

Besides the aforementioned five INP methods, there are other WCPS-specific INP methods including different degree of data compression and local data filtering. Different INP methods in WCPS will lead to different tradeoff among different QoS metrics. These tradeoffs tend to be application specific and to study the joint optimization on QoS and these new INP methods can provide support the close-loop control in WCPS.

C. Cooperation of Different INP Methods in WCPS

The community has started to studied the trade-off between QoS and single INP method in WCPS. Some work [26][6][43] also proposed whole system architectures that cooperate INP with existing network protocol stack. However, how to apply different INP methods together in one system is still an open area. A simple example will show that this approach can further improve the system performance. Suppose intra-flow coding is adopted in wireless networks. After a node did intra-flow network coding for a few packets, it can further pack these coded packets together using packet packing method. In this way, the total ETX can be further reduced. Since INP methods all aims to reduce the traffic load in WCPS, studying the cooperation between different INP methods is a promising direction to provide QoS-guaranteed performance for WCPS. However, characteristics and major concerns of different INP methods can make the cooperation hard. For example, query processing mainly aims to guarantee the data accuracy while data aggregation mainly considers how to minimize energy consumption. Thus it is a challenging task to balance these two goals.

D. Theoretical Foundations of Algorithm

The research on QoS-aware INP design in WCPS is a new area. Due to the different characteristic between WCPS and other wireless networks, traditional network optimization theory are not enough to provide mathematical tools for this area. For example, traditional network-flow perspective mainly studied the static network flow model. However, many applications in WCPS have high mobilities. Cai *et al.* [5] studied the time-varying network flow problem in a dynamic programming approach. Though it mainly focused on the time-varying change along network edges while INP emphasizes data processing on network nodes, it could give a guideline for QoS-assured INP data flow control in WCPS.

V. CONCLUSION

We presented a comprehensive survey of INP methods and QoS-aware INP design in WCPS. INP techniques are adopted in WCPS with the main goal of minimizing energy consumption. In Section II, different INP protocols are investigated according to the category they belong to. Due to the mission-criticality and real-time requirement of many WCPS, how to design energy-efficient INP protocol while assuring different QoS constraints becomes a new challenge for the community and only a few works have been done in this area. In Section III, these works are introduced and summarized according to different QoS metrics.

In Section IV, some possible research directions in this area are discussed, including both theoretical research and concrete protocol design. With both the quick development of WCPS and its high similarity with WSN and general wireless networks, it is expected that INP continue play an important role in WCPS. Nonetheless, the unique characteristics of WCPS, e.g., using system output for closed-loop control, differentiate them from traditional WSN and wireless networks and suggest the importance of QoS guarantee in INP. Therefore, to study how to design QoS-assured INP protocols in WCPS is a challenging and urgent area for future research.

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