Collaborative Opportunistic Network Coding for Persistent Data Stream in Disruptive Sensor Networks

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***Abstract*—In an energy-harvesting sensor network for perpetual lifetime, the operation of sensor nodes are synchronized with the energy fluctuations, causing the network connectivity to be disruptive and unstable. The unpredictable network disruptions and challenging communication environments make the traditional communication protocols inefficient and require a new paradigm-shift in design. In this thesis, we address several issues in collaborative data collection and storage in disruptive sensor networks. Our solutions are based on erasure codes and probabilistic network coding operations. The proposed set of algorithms improve data throughput and persistency because they are inherently amenable to probabilistic nature of transmission in wireless networks. Our contributions consist of five parts. First, we propose a collaborative data delivery protocol to exploit multiple energy-synchronized paths based on a new max-flow min-variance algorithm. In consort with this data delivery protocol, a localized TDMA MAC protocol is designed to synchronize nodes' duty-cycles and mitigate media access contentions. Second, we present Opportunistic Network Erasure Coding protocol, to collaboratively collect data in dynamic disruptive networks. ONEC derives the probability distribution of coding degree in each node and enable opportunistic in-network recoding, and guarantee the recovery of original sensor data can be achieved with high probability upon receiving any sufficient amount of encoded packets. Third, we present OnCode, an opportunistic in-network data coding and delivery protocol that provides good quality of services of data delivery under the constraints of energy synchronization. It is resilient to packet loss and network disruptions, and does not require any end-to-end feedback message. Fourth, we present a network Erasure Coding with randomized Power Control (ECPC) mechanism for data persistence in disruptive sensor networks, which only requires each node to perform a single broadcast at each of its several randomly selected power levels. Thus it incurs low communication overhead. Finally, we study an integrated algorithm and protocol middleware to preserve data persistency with heterogeneous disruption probabilities across the network.**

***Index Terms*—Persistent Data Collection, Network Erasure Coding, Transmission Power Control, Disruptive Sensor Network**

I. Introduction to Doctoral Thesis

Sensor networks are key technology to enable critical applications in catastrophic or emergency scenarios [1], such as floods, fires, volcanos, battlefields, where human participation is too dangerous and infrastructure networks are impossible or too expensive. However, those challenging environments pose severe challenges to network sustainability and reliability. Without ambiguity, we name this extreme network environment as Disruptive Sensor Networks. In disruptive sensor networks, a predictable and stable path may never exist, the network connectivity is intermittent, and a node could suddenly appear or disappear. In the other hand, since the deployment environment is challenging and man power for replacing battery power supply is costly and unmanageable. The energy self-supply technology, like energy harvesting from environment is suggested and adopted. In such an energy-harvesting sensor network for perpetual lifetime, the operation of sensor nodes are synchronized with the energy fluctuations, causing the network connectivity to be disruptive as well. The unpredictable network disruptions and challenging communication environments make the traditional communication protocols inefficient and require a new paradigm-shift in design. Recent studies propose a class of coding schemes based on erasure codes. Such coding eliminates the dependency of feedback and achieves efficient data collection of high reliability in disruptive sensor networks. In this thesis, we solve important issues of collaborative data collection and storage in disruptive sensor networks. Our solutions are based on erasure codes and probabilistic network coding operations. The proposed set of algorithms improve data throughput and persistency because the algorithms are inherently amenable to probabilistic nature of transmission in wireless networks.

Our contributions consist of five parts. First, we propose an innovative system design where nodes collaboratively utilize the heterogenous duty-cycles to maximize network performance while meeting network lifetime constraints. We propose a collaborative data delivery protocol to exploit multiple energy-synchronized paths based on a new max-flow min-variance algorithm [2]. The main technical contributions of this component are: a collaborative data delivery protocol is designed to maximize network throughput and fairness and synchronize nodes duty-cycles for efficient communications. Moreover, in consort with the collaborative data delivery, a localized TDMA MAC protocol is designed, which synchronizes nodes' duty-cycles and eliminate media contention for efficient communication on the selected flow paths. For time synchronization, in our platform, a radio receiver is attached to provide millisecond synchronization accuracy with μA current consumption. Extensive evaluations are conducted in both real test-beds and network simulators. The results demonstrate that this design not only increases network throughput and fairness, but also increases network lifetime, comparing to an existing protocol stack of X-MAC [3] and CTP [4].

Second, we present Opportunistic Network Erasure Coding protocol [5], to collaboratively collect data in dynamic disruptive networks. ONEC establishes a theoretic foundation of opportunistic network coding in this work and thesis. ONEC is designed to transform the "end-to-end" paradigm of LT codes(Luby Transform) [6] to "many-to-one" network LT codes. ONEC adopts recursive decomposition structure to conduct probability distribution deconvolution, supporting heterogeneous symbol sizes in each source nodes. ONEC derives the probability distribution of coding degree in each node and enable opportunistic in-network recoding, and guarantee the recovery of original sensor data can be achieved with high probability upon receiving any sufficient amount of encoded packets. The performance evaluation through simulation validates that ONEC truly achieve high reliability of data collection in disruptive networks and outperforms other existing approaches.

Third, we present OnCode, an opportunistic in-network data coding and delivery protocol that provides good quality of services of data delivery under the energy constraints. It is resilient to packet loss and network disruptions, and does not require any end-to-end feedback message. Moreover, it provides good Quality of Services (QoS) of data delivery in wireless sensor networks. In principle, OnCode self-tunes the encoding block to adapts to dynamic source data rates and ON/OFF wake-on ratios from ambient neighbor nodes. Moreover, OnCode adapts the probabilistic forwarding *in-situ* to energy variations. It exploits randomized structure-free data coding and delivery mechanism, and is resilient to packet loss and network disruptions.

In the literature, designing efficient data delivery protocol, which fully take advantages of both heterogeneous nodal energy constraints and transmission opportunities, remains under-explored. An appropriate protocol design needs to allow for the unpredictable disruptions due to nodal energy constraints, and at the same time utilize opportunistic transmission with minimum cost. To the best of our knowledge, OnCode is the first work that explores opportunistic network coding to synchronizes data delivery operation with dynamic nature of renewable energy constraints, without the need of determined routing structure underneath. This work presents a comprehensive implementation, deployment, and evaluation of proof-of-concept prototype of OnCode on testbed.

Fourth, we further present an integrated algorithm to preserve data persistence (*Ravine Streams*) with both heterogeneous energy constraints and constrained storage space. To preserve data persistence, data stream has to be rerouted to other paths or redistributed to other storage nodes if storage space in nodes are overflowed. For data preservation, receiving nodes distributively make the acceptance decision based on local failure probability and storage space. Note that here nodal failure probability has taken the residual energy into account and dynamically update across the process. Adaptive transmission power control in *RS* ensures that data acceptance probability by neighbor nodes is expected at $O(1)$ for each broadcasting under minimum transmission power. With data packet recoding, the dispensable data content redundancy is constrained for more energy efficiency.

Finally, we present a network Erasure Coding based storage scheme with randomized Power Control (ECPC) mechanism. Its goal is to store and preserve as much data as possible inside networks during the down time of base station. It only requires each node to perform a single broadcast at each of its several randomly selected power levels. Thus it incurs low communication overhead as well as storage cost. ECPC makes a distinction from the literature: it achieves downtime data persistence only by localized data packet broadcasting and erasure coding. Performance comparisons show that ECPC mechanism reaches higher data reliability under varying node failure probabilities. In addition, our approach is scalable and has low communication overhead.

This doctoral thesis proposes a set of algorithm based on network erasure coding theory to improve the data quality and preserve data persistence in disruptive wireless sensor networks. Max-flow min-variance algorithm schedule flows among multiple energy-synchronized data paths without coding techniques. It established a benchmark for optimal solution. Due to network dynamics and heterogeneous disruption across network, opportunistic routing and coding is studied to practically preserve data persistence. ONEC lays a theoretic foundation for later three works, with respect to the degree deconvolution and applying erasure codes to network codings. The coding overhead is minimized because the advantageous statistical property of erasure codes is well preserved in our proposed network codings. And OnCode is proposed to provide good quality of data service under the constraints of energy synchronization. The Ravine Streams simultaneously consider the constrained of energy and limited storage space in disruptive sensor networks. ECPC addresses the problem of data storage when sink node becomes unavailable.

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