Intelligent Adaptation in Data Intensive Sensor Networks

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Highly distributed and resource-constrained networked environments can be studied and optimized as complex adaptive systems (CAS). CAS is formed out of many elements whose behavior is emergent. That is, the behavior of the system cannot be simply inferred from the behavior of its elements. The collective behavior of the elements results in emergent complexity, where simple localized interactions between individual elements converge to a global pattern reflecting changing environmental conditions.

Complex adaptive systems manifest themselves in various fields and under diverse topics. This includes distributed constraint-satisfaction, multi-agent systems, distributed cooperation, game theory, non-linear dynamics, etc. Some common examples of CAS are *stock markets* where buyers, sellers and the market adapt to economic conditions and each-other's actions; *harvester-ant colonies* that show the emergence of colonies from relatively simple tasks performed by the ants; and *virus life-cycle in the ecosystem* where a virus depletes a species that leads to shortage of food-supply for other virus and in turn, limits the virus behavior.

A large-scale distributed information system can also be considered as a complex system where connections and interactions between its components provide the ability to deliver and process data. In particular, wireless and mobile environments maintain such connections via ad-hoc links in a neighborhood, which tend to be highly dynamic and unpredictable. Furthermore, the resource constraints (channel capacity, protocol limitations, buffer capacity, and energy availability) may cause notable information losses. Optimizing information delivery in such environments is challenging, since factors impacting successful information delivery are numerous and their combined effect is hard to assess for different network configurations and application scenarios. This is a major reason why traditional cost-based optimization approaches using refined system models have limited applicability in large-scale distributed information systems.

We propose to consider alternative optimization strategy treating complex distributed system as a CAS and utilizing the emergent complexity to adapt to highly dynamic environments via light-weight localized adjustments of the interaction between its elements. This approach can be illustrated on a case study of Data Intensive Sensor Networks (DISNs) for applications with high bandwidth needs (e.g., continuous monitoring of the integrity of civil and military structures, dynamic emergency assessment, disaster management, fire evacuation, etc.). The well-known resource constraints have a much stronger impact in DISNs and their performance dramatically degrades with increase in network size and data rate.

To meet the application requirements, the DISN should provide more sustainable information delivery as the network size and data rates increase. While numerous techniques were proposed to handle data losses due to link quality degradation, congestions, no route availability, and packet collisions, it is not feasible even for relatively small sensornets to explicitly tune up and optimize the complex interplay between those factors. The alternative light-weight adaptive approach can improve performance of data intensive sensornets. Instead of relying on a refined network cost model that would account for various data losses, the adaptive approach optimizes information delivery in DISN using a "macroscopic" view of the network as a CAS, where localized decisions made by individual sensors converge to a desirable information delivery pattern. Such simple adaptive actions performed by each sensor with respect to the locally-observable network conditions can result in the emergent network behavior that reflects notable performance improvement.

Exploring this emergent behavior of the DISN we recognize that various reasons for information loss in a sensornet are collectively manifested as WSN *bottlenecks.* A bottleneck is formed by one or several sensor nodes interfering with the rest of the network without contributing to the successful delivery of data. In general, detecting bottlenecks is hard. It would require intensive WSN self-monitoring and may be prohibitively expensive for resource-constrained sensornets. Besides, even after being successfully detected, the bottleneck resolution would need even more considerable efforts in network assessment and analysis. Performing it in real time on the top of a heavily-loaded DISN is not realistic. Meanwhile, the adaptive strategy automatically detects and resolves the WSN bottlenecks. For example, sensor nodes can tune up their information delivery according to their contribution to successfully delivered data. One way to achieve that goal is to make sensors transmit only if they have some confidence that the data will be delivered successfully. This goal can be achieved via localized dynamic rate adaptation. The adaptive approach improves not only the ratio of successfully delivered data packets, but also leads to larger amounts of data delivered to the sink.

Different formalisms that can facilitate localized decision making in CAS. For example localized rate adaptation in DISN can be formalized as Markov Decision Process (MDP). MDP aims to influence the behavior of a dynamic probabilistic system. An MDP model defines system states, actions, state transition probabilities and expected rewards for actions performed in specific states. The decisions on choosing an optimal action in a current state are made at time points called decision epochs. Choosing action a in state s results in a reward $r(s, a)$. System state si at the next decision epoch depends on the transition probability distribution $p(si|s,a)$. A decision policy prescribes action selection at each state at all decision epoch. Depending on whether the number of decision epochs is finite or infinite, the model is finite horizon or infinite horizon correspondingly.

The localized rate adaptation in DISNs can be represented as an infinite horizon MDP with rewards and transition probabilities reflecting more aggressive or conservative network behavior. The transition probabilites can be assigned for different generic network configurations and application requirements. An MDP model can be solved to find an adaptation policy that accumulates highest reward. Choosing appropriate rewards for states and actions, we can tune the policy selection process to achieve desired *performance targets*. For example, if each node maintains low data rate in each state the network would live longer while transmitting a low amount of data fairly successfully. We can reflect this conservative approach with a set of rewards that lead the MDP model to generate a conservative policy.

We believe that the light-weight adaptive strategies can be efficiently applied for wide class of large-scale wireless and mobile information systems.