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Timeliness Issues of Duty-Cycled MAC Protocols: Toward Energy and Timely Constrained Data Delivery in Wireless Sensor Networks

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Abstract

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Nowadays it has become possible to build tiny, wireless communication enabled, hardware devices, for monitoring and measuring miscellaneous parameters of the environment. This yields Wireless Sensor Networks (WSNs); a special class of wireless networks where nodes are low cost, resource constrained, and generally battery powered devices. Energy-efficiency is the main concern in most wireless sensor network applications. When in idle mode, current radios consume as much energy as when transmitting or receiving data, thus only by putting the radio into sleep mode that the energy consumption is reduced considerably, and allowing 99% of data delivery with duty cycles below 1%. This remarkable energy conservation is thus achieved at the MAC layer using duty-cycling of the radio (i.e, switching between active/sleep modes). In active mode, a node can receive and transmit packets. While in the sleep mode, it completely turns off its radio to save energy. In this situation, a node needs to be aware of its neighbors' wakeup time, since packets cannot be exchanged unless both the transmitter and the receiver are awake. This has a direct impact on the forwarding delay of sensed data. Ensuring low-latency in large scale WSN is challenging, due to sensor nodes' limitations in energy supply, communication capabilities and unstable wireless links. The end-to-end (e2e) delay is the most critical factor in time-constrained monitoring applications, where a high priority data needs to be reported to a sink in time so that the appropriate action can be taken immediately. This thesis deals with timeliness issues in energy constrained WSN in the case of low data rate applications.

This thesis begins with an overview on the delay performance in the context of energy-limited WSN, where energy is considered as a constraint for MAC protocols that inevitably duty-cycle the radio. In this part of the thesis, we provide a comprehensive review and taxonomy of state-of-the-art *synchronous* and *asynchronous* contention-based low duty-cycle MAC protocols which are typically implemented in many WSN applications. The main objective is to study and classify these protocols from the delay efficiency perspective. In synchronous schemes, protocols can be divided into five categories: static grouped schedule, adaptive grouped schedule, adaptive repeated schedule, staggered schedule, and reservation schedule. While asynchronous

protocols can be also divided into five categories: static preamble sampling, adaptive preamble sampling, collaborative schedule setting, beacon-based, and anticipation-based protocols. Several state-of-the-art protocols are described following the proposed classification, with comprehensive discussions and comparisons with respect to their latency.

In the second part, we propose a novel asynchronous cascading wakeup MAC protocol for heterogeneous traffic gathering. It jointly considers energy/delay optimization and switches between low duty-cycle (LDC) and high duty cycle (HDC) modes, according to the traffic type and delay requirements. The proposed protocol, named DuoMAC, has the following features: it adjusts the wake-up of a node according to (i) its parent's wake-up time and, (ii) its estimated load. It incorporates a service differentiation through an improved contention window adaptation to meet delay requirements. The protocol is analyzed and compared with some state-of-the-art energy-delay efficient MAC protocols. Dynamic parameter adaptation mechanism has been integrated to DuoMAC to balance the delay and energy objectives at runtime. DuoMAC has been implemented on real motes using MicaZ and experiments reveal that the runtime parameter adaptation provides additional reduction of the latency while further decreasing the energy cost.

Besides the design of efficient communication protocols, optimizing energy consumption and end-to-end delay in energy-constrained WSNs is a conflicting multi-objective problem. In the third part of the thesis, the energy-delay tradeoff is investigated from the game theory perspective, where an optimization framework based on Nash Bargaining and Kalai-Smorodinsky Bargaining models, provides the optimal energy-delay balancing solution given the application requirements and allows to set tunable system parameters to reach a fair equilibrium point which dually minimizes the system latency and energy-consumption. For illustration, this formulation is applied to our proposed MAC, DuoMAC, as well as to five state-of-the-art WSN MAC protocols; B-MAC, X-MAC, RI-MAC, SMAC, and LMAC. Further, we have carried out an extensive set of simulations to validate the optimization results where the energy consumption and the average e2e delay were measured and compared to the analytical results. We found that when tuning protocols with optimal parameters, they map the obtained trade-off performances and confirm the effectiveness of the proposed framework.

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