

Cross-layer Optimization in Sensor Networks with Energy Constraints

Shuguang Cui and Andrea J. Goldsmith

I. RESULTS SUMMARY

A typical wireless sensor network consists of sensors powered by small batteries that are difficult to replace if not impossible. Hence, the sensor nodes can only transmit a finite number of bits before they run out of energy. Thus, reducing the energy consumption per bit for end-to-end data transmission is an important design consideration for such networks. We assume that each information bit collected by a sensor is useful for a finite amount of time; after this time the information may become irrelevant. Hence all the bits collected by the sensors need to be communicated to a hub node before a certain deadline. Therefore, the maximum end-to-end transmission delay for each bit must be controlled to meet a given deadline under the hard energy constraint. Since all layers of the protocol stack affect the energy consumption and delay for the end-to-end transmission of each bit, an efficient system requires a joint design across all these layers as well as the underlying hardware where the energy is actually expended [1]. In our work [2]-[11], we show that joint design optimization across hardware, link layer, MAC, and routing is a beneficial and feasible approach to implement an efficient energy-constrained wireless network.

We start with a point-to-point link [2]-[4], where we minimize the total energy consumption for transmitting a given number of bits by considering both the transmission energy and the circuit processing energy. We have shown that the traditional belief that a longer transmission duration lowers energy consumption may be misleading if the circuit energy consumption is considered, especially for short-range applications. For both MQAM and MFSK, we show that the transmission energy is completely dependent on the product of the transmission bandwidth and the transmission time. To minimize the transmission energy, maximum transmission time is required. To minimize the total energy consumption, the transmission time needs to be optimized, where we show that significant energy savings is achievable via this optimization. For trellis-coded narrow-band MQAM systems, we have shown that coding always increases energy efficiency, and the improvement increases with the transmission distance d . For MFSK systems, coding can only reduce energy consumption when the transmission distance is large such that the transmission energy is dominant. For short-range applications, uncoded MFSK outperforms coded MFSK due to the bandwidth expansion caused by the error control code. We found

that uncoded MQAM is not only more bandwidth-efficient, but also more energy-efficient than uncoded MFSK for short-range applications. The performance difference is even more pronounced with coding. However, coded MFSK may be desirable in peak-power-limited applications since it requires less transmit power, although its total energy consumption may be higher.

We then consider a Multiple Access (MAC) scenario [5], where multiple sensor nodes are sending data to a central node. By jointly designing the MAC layer and the link layer considering hardware constraints, we propose a variable-length Time Division Multiple Access (TDMA) scheme to minimize the total energy consumption. Significant energy savings is achieved compared with the traditional uniform TDMA scheme.

To push further, we look at the joint design optimization across hardware, link layer, MAC, and routing. We first focus on the interference-free case where we use a variable-length TDMA scheme in the MAC layer (see [6]-[9]). We show that if link adaptation is not allowed, the energy minimization problem is a convex problem and can be efficiently solved. If link adaptation is allowed, the energy minimization problem can be relaxed to a convex problem and efficient algorithms exist to achieve a near-optimal solution. The results show that significant energy savings is possible compared with traditional MAC and routing schemes that are based on layered structures. We also show that when only the transmission energy is considered, multihop routing saves energy. However, when the circuit processing energy is considered, single-hop transmissions may be more efficient than multihop routing schemes. Link adaptation is shown to be able to further improve the energy efficiency when jointly designed with MAC and routing. Numerical examples show that significant energy savings is possible when link adaptation is included in the design model. In addition, link adaptation may reduce the transmission time in relay nodes by using higher constellation sizes such that the extra circuit energy consumption in the relay nodes is reduced. As a result, multihop routing may become more energy-efficient than single-hop transmissions when link adaptation is used.

In [8] and [9], we analyze the delay performance of transmission schemes using variable-length TDMA. We propose a simple link scheduling algorithm to find the minimum-delay schedule given the slot lengths for all the links. We then combine these results with our previous work on energy-optimal cross-layer design to minimize the delay in transferring a fixed number of bits from the source nodes to the sink, in an energy-constrained manner. We also study the tradeoff between the

S. Cui and A. J. Goldsmith are with the Wireless System Lab, Department of Electrical Engineering, Stanford University, Stanford, CA 94305. Emails: {shuguang, andrea}@wsl.stanford.edu.

total energy consumption and delay. Pareto-optimal energy-delay curves are computed by solving a series of convex optimization problems where each objective function is a weighted sum of the delay and the total energy consumption. The computation is done for networks with and without link adaptation capabilities. In [10] and [11], we extend the joint routing, MAC, and link layer optimization problem to the case where non-orthogonal MAC schemes are used such that interference between different transmission links becomes a performance-limiting factor. We show that even though the overall problem is not convex, significant energy savings is still possible by approximating the optimal solution with some relaxation methods.

We also show that the cross-layer approach can be extended horizontally to allow the cooperation among multiple nodes [12]. Virtual MIMO systems can be constructed via node cooperation on both the transmitting side and the receiving side. Numerical examples show that energy saving and delay reduction can be achieved at the same time within a certain transmission range by deploying such cooperative MIMO systems, even when we consider the extra energy/delay penalty caused by the local information exchange.

We also investigate joint estimation problems in an energy-constrained sensor network (see [13] and [14]), where we consider the source coding and the channel coding jointly. We consider the problem of optimal power scheduling for the decentralized estimation of a noise-corrupted signal in an inhomogeneous sensor network. Sensor observations are first quantized into discrete messages, then transmitted to the fusion center where a final estimate is generated. Based on the sensor noise levels and channel gains from sensors to the fusion center, optimal quantization levels and transmit power levels at local sensors can be chosen to minimize the total transmit power, while ensuring a given Mean Squared Error (MSE) performance. The proposed optimal power scheduling scheme suggests that the sensors with bad channels or poor observation qualities should decrease their quantization resolutions or simply become inactive in order to conserve power. For the remaining active sensors, their optimal quantization and transmit power levels are determined jointly by individual channel gains, local observation noise variance, and the targeted MSE performance. Numerical examples show that significant energy saving is possible when compared with the uniform quantization strategy. We have also proposed a pure analog approach for the joint estimation problem [15]. We compare the energy efficiency of this analog approach with digital approaches with and without coding. We show that the analog approach is more energy-efficient than the digital system without coding and in some cases beats the digital system with optimal coding.

II. FUTURE WORK

We will continue the joint routing, MAC, and link layer optimization problem for the interference-limited case, where the benefit of frequency reuse will be further investigated. We will also combine cooperative MIMO techniques into the routing scenarios, where MIMO gains can be explored to

reduce energy consumption. For the joint estimation problem, we will investigate the optimal joint source and channel coding schemes under certain distortion requirement, for which code or not to code is still unclear.

REFERENCES

- [1] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained Ad Hoc wireless networks," *IEEE Wireless Communications Magazine*, pp. 8-27 Aug. 2002.
- [2] S. Cui, A. J. Goldsmith, and A. Bahai, "Modulation optimization under energy constraints" at *Proceedings of ICC'03*, Alaska, U.S.A, May, 2003. Also available at <http://wsl.stanford.edu/Publications.html>
- [3] —, "Energy-constrained Modulation Optimization for Coded Systems," at *Proceedings of Globecom'03*, San Francisco, U.S.A, December, 2003. Also available at <http://wsl.stanford.edu/Publications.html>
- [4] —, "Energy-constrained modulation optimization," to appear at *IEEE Trans. on Wireless Communications*, 2004. Also available at <http://wsl.stanford.edu/Publications.html>
- [5] —, "Joint modulation and multiple access optimization under energy constraints," at *Proceedings of Globecom'04*, 2004. Also available at <http://wsl.stanford.edu/Publications.html>
- [6] S. Cui, R. Madan, S. Lall, and A. J. Goldsmith, "Joint routing, MAC, and link layer optimization in sensor networks with energy constraints," to appear at *ICC'05*, South Korea, May, 2005. Also available at <http://wsl.stanford.edu/Publications.html>
- [7] —, "Cross-layer Optimization in TDMA-based Sensor Networks with Energy Constraints," submitted to *IEEE Trans. on Wireless Communications*, 2004. Also available at <http://wsl.stanford.edu/Publications.html>
- [8] —, "Energy-delay tradeoffs in TDMA-based sensor networks," to appear at *ICC'05*, South Korea, May, 2005. Also available at <http://wsl.stanford.edu/Publications.html>
- [9] —, "Energy Minimization and Delay Analysis in TDMA-based Sensor Networks," submitted to *IEEE Trans. on Wireless Communications*, 2004. Also available at <http://wsl.stanford.edu/Publications.html>
- [10] R. Madan, S. Cui, S. Lall, and A. J. Goldsmith, "Cross-layer design for lifetime maximization in interference-limited wireless sensor networks," to appear at *IEEE Infocom'05*, Florida, 2005.
- [11] —, "Mixed Integer-Linear Programming for Link Scheduling in Interference-Limited Networks," submitted to *IEEE 1st workshop on Resource Allocation in Wireless Networks*, Italy, April, 2005.
- [12] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and Cooperative MIMO in Sensor Networks," at *IEEE Journal on Selected Areas of Communications*, Vol. 22, No. 6, August, 2004. Also available at <http://wsl.stanford.edu/Publications.html>
- [13] J. Xiao, S. Cui, Z. Q. Luo, and A. J. Goldsmith, "Joint Estimation in Sensor Networks under Energy Constraint," at *Proceedings of IEEE first conference on Sensor and Ad Hoc Communications and Networks*, Santa Clara, CA, October, 2004.
- [14] —, "Joint Estimation in Sensor Networks under Energy Constraint," submitted to the *IEEE Transactions on Signal Processing*, 2004 (under revision).
- [15] S. Cui, J. Xiao, A. J. Goldsmith, Z. Q. Luo, and H. V. Poor, "Energy-Efficient Joint Estimation in Sensor Networks: Analog vs. Digital," to appear at *IEEE ICASSP*, Philadelphia, PA, 2005.