Energy Efficient Protocols for Low Duty Cycle Wireless Microsensor Networks

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Abstract— **Emerging distributed wireless microsensor networks will enable the reliable and fault tolerant monitoring of the environment. Such microsensors are required to operate for years from a small energy source, while maintaining reliable communication link to the basestation. The design of energy-aware communication protocols can have a dramatic impact on the network lifetime for such applications. A detailed communication energy model, obtained from measurements, is introduced that incorporates the non-ideal behavior of the physical layer electronics. This includes the start-up energy cost of the RF tranceiver, which dominates energy dissipation for short packet sizes. Using this model, various communication layer protocols are explored for asymmetrical sensor networks such as machine monitoring. The paper also proposes the use of a variable bandwidth allocation scheme, that exploits spatial distribution of sensors.**

I. Introduction

The design of micropower wireless sensor systems have gained increasing importance for a variety of civil and military applications. Wireless microsensor networks will enable the reliable monitoring of a variety of applications that range from medical and home security to machine diagnosis and chemical/biological detection. Over the past few years, there has been significant research in distributed sensor networks. A number of interesting results have been published for a wide range of technical areas, from signal processing and communication protocols such as multi-hop routing and data fusion techniques to physical layer circuit implementations [1], [2], [3]. The work published on communication protocols are primarily aimed at increasing the QoS and energy efficiency of general ad-hoc collaborative sensor networks through optimizations above the link layer. In this work, we specifically look at an asymmetrical sensor network where clusters(i.e. cells) are formed around high powered basestations. Energy constrained sensors communicate to high powered basestation in their cluster. An example of such a network is machine diagnosis in an industrial setting.

The constraints of these sensors are quite different from those of conventional wireless hand-held devices in addition to their small size and ultra low power consumption. First of all, sensors have a much lower data rate (<kbps) and packet size (tens of bits) when compared to multimedia traffic. Second, the communication link is highly asymmetric (i.e. traffic is mostly uplink from the sensor to the basestation). Third, a cell covers a small area (<10m) and the *cell density*(i.e. number of sensors per cell) can have a large spatial variation and small time variation. That is, one cell may have a few hundreds of sensors while another cell only has a few number of sensors. Finally, reliability (low packet error rate) and latency requirements of the transmitted packet are also important design parameters in the implementation of energy efficient microsensor network. This paper explores techniques to lower the power consumption for such environment monitoring applications based on models which are extracted from physical layer electronics.

II. Communication Protocol

A. Low Power Media Access Protocol

In this section, we limit our choice of media access control (MAC) protocol to time division multiple access (TDMA) and frequency division multiple access (FDMA).

A.1 Radio Model

The average power consumption of a sensor radio is given by the following equation, where $N_{tx/rx}$ is the average number of times per second that the sensor transmitter/receiver is used, which is specified by the application scenario and communication protocol, $P_{tx/rx}$ is the power consumption of the transceiver, $T_{on-tx/rx}$ is the transmit/receive on-time (actual data transmission/reception time), $T_{startup}$ is the start up time of the transceiver, and P_{out} is the output transmit power which drives the antenna.

$$\begin{aligned} P_{avg} &= N_{tx}\{P_{tx}(T_{on-tx}+T_{startup})+P_{out}T_{on-tx}\} \\ &+ N_{rx}P_{rx}(T_{on-rx}+T_{startup}) \end{aligned} \tag{1}$$

Before a detailed MAC protocol is developed, the following issues must be considered. First, it should be noted that power consumption of the transceiver dominates over the output transmit power($P_{tx/rx} \ll P_{out}$). When transmitting data over a short distance(<10m) power consumption of the radio electronics is dominated by the analog RF circuitry which typically consumes 10s $\sim$ 100s of milliwatts(mW) [4], [5]. On the other hand the output transmit power(P_{out}) consumes less than 1mW for BER as low as 10^{-6} [6]. In addition, the transmitter power(P_{tx}) does

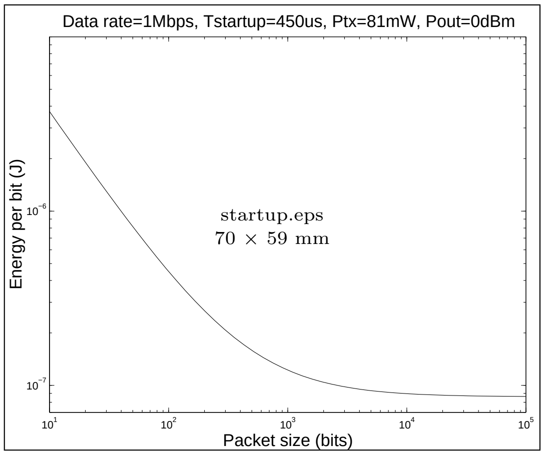

Fig. 1. Effect of startup transient

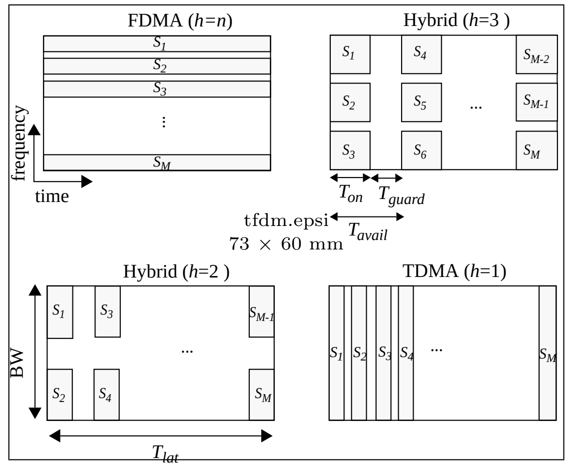

Fig. 2. Multiple access methods

not vary much over data rate to a first order approximation. In GHz frequency bands, power consumption of the transceiver is dominated by the frequency synthesizer which generates the carrier frequency and it is not effected by the data rate to the first order [7]. Hence for low power operation, it is desirable to send the data at maximum rate in order to reduce the transmit on-time (T_{on-tx}). Second, the startup time ($T_{startup}$) should receive special attention due to the short packet size. In order to save power, the radio module needs to be turned on/off during the active/idle periods (i.e. duty cycled). Unfortunately transceivers today require initial startup times on the order of hundreds of microseconds to go from the sleep state to the active state. For short packet sizes, the transient energy during the start-up can be significantly higher than the energy required by the electronics during the actual transmission (i.e. $T_{startup} > T_{on-tx}$). This effect of startup transient is shown in Figure 1, where energy consumption per bit is plotted versus packet size. This is achieved from a commercial low power tranceiver [4] which is capable of transmitting data up to 1Mbps while consuming 81mW. We see that as the packet size is reduced, the energy consumption is dominated by the startup transient($T_{startup}$) and not by the transmit on time(T_{on-tx}). Hence it is important to take this inefficiency into account when designing energy aware communication protocols. Lastly, although the data traffic is mostly uplink from the sensors to the basestation, downlink may also be necessary for certain protocols. That is, N_{tx} is governed by the application scenario and N_{rx} is determined by the protocol. It should also be noted that P_{rx} is usually $2 \sim 3$ times higher than P_{tx} in typical commercial radios and hence MAC protocol should try to avoid high receiver activity.

A.2 TDMA-FDMA

In this section we derive a low power MAC protocol based on the radio model from Eq. 1 for a single cell network where a high-powered basestation gathers data from the sensors. Assuming we have control over data rate, T_{on} is minimized in TDMA since the bandwidth is at maximum, allowing the highest data rate. For FDMA, the available bandwidth is at minimum, resulting in the longest on-time. A hybrid scheme of TDM-FDM is also possible, where both time and frequency are divided into transmission slots. This is illustrated in Figure 2 where shaded area indicates a valid transmit slot for sensor S_i. In cases where time division is employed, we should note that a downlink from the basestation to the sensors is required in order to maintain time synchronization among the sensors. Due to the finite error among each sensor's reference clock, the basestation must send out *sync* signals as to avoid any collision among the transmitted packets. Hence the sensor receiver must be turned on every so often to receive these *sync* packets. The number of receptions (N_{rx}) depends on the guard time (T_{guard}) which is the minimum time difference between two time slots in the same frequency band, as shown in Figure 2. If two slots in the same frequency band are separated by T_{guard}, it will take T_{guard}/ρ time for these two packets to collide, where ρ is the difference between the two reference clocks. Hence the sensor must be resynchronized at least ρ/T_{guard} number of times every second. This is described in Eq. 2, where BW is the total available bandwidth, $Data$ is the size of the transmit packet in bits, T_{lat} is the latency requirement of the sensor data, h is the number of channels in the given BW, T_{avail} is the time difference between start of two packets (Figure 2 and M is the number of sensors. It is also assumed that the data rate is equal to the occupying signal bandwidth and hence $T_{on} = Data/(BW/h)$.

$$N_{rx} = \frac{\rho}{T_{guard}} = \frac{\rho}{T_{avail} - T_{on}} = \frac{\rho}{(\frac{T_{lat}}{M} - \frac{Data}{BW})h} \quad (2)$$

From the above equation, we see that as the number of channels decreases, guard time becomes larger and receiver activity is reduced. It is also apparent that the advantage of pure FDMA is that it does not need a receiver (i.e. $T_{guard} \to \infty, N_{rx} = 0$).

By plugging in Eq. 2 into Eq. 3, we can find an analytical formula for the optimum number of channels which gives

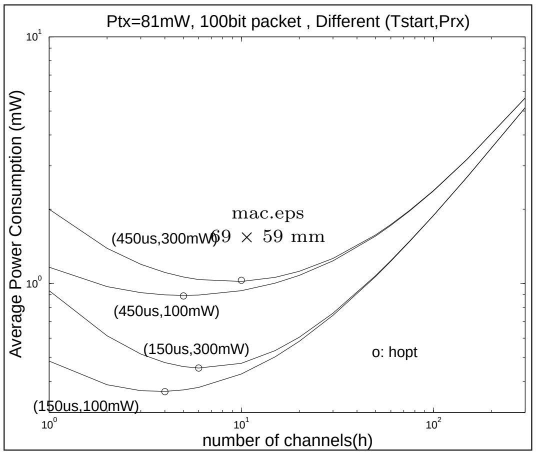

Fig. 3. Energy with different $(T_{startup}, P_{rx})$

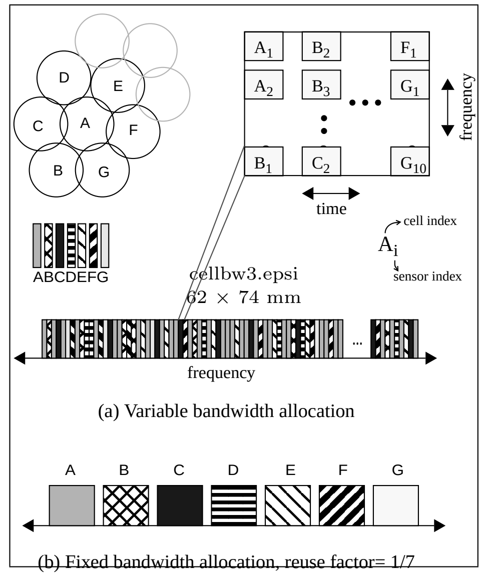

Fig. 4. Bandwidth allocation schemes

the minimum power. This is given in Eq. 3, where in addition to the previous notations, h_{opt} represents the optimum number of channels to achieve lowest power consumption.

$$\begin{aligned} h_{opt} &= \sqrt{\frac{\delta P_{rx}(T_{on-rx} + T_{startup-rx})}{(\frac{T_{lat}}{M} - \frac{Data}{BW})N_{tx}(P_{tx} + P_{out})\frac{Data}{BW}}} \\ &\propto \sqrt{\frac{P_{rx}}{N_{tx}P_{tx}}} \end{aligned} \quad (3)$$

We see that h_{opt} is determined by the power consumption ratios between the transmitter and the receiver. As expected, receivers which consume less power favors TDMA with less number of channels, while receivers with larger power prefers FDMA with larger number of channels.

An example of the previous analysis is performed in a scenario where a sensor on average sends twenty 100-bit packets/sec ($N_{tx} = 20/sec, Data = 100bits$) with $5ms$ latency requirement ($T_{lat} = 5ms$). The bandwidth available to the cell is 10MHz ($BW = 10MHz$), and the number of sensors is 300. The resulting average power consumption is plotted in Figure 3, where average power consumption is plotted versus the number of channels (i.e., $h = 1$: TDMA, $h = 300$: FDMA). The graph shows power consumption for different P_{rx}/P_{tx} and $T_{startup}$. It can be seen that h_{opt} increases for higher receiver power, as to reduce the number of receptions. Again, the reason why TDMA with minimum on-time does not achieve the lowest power is because of the receiver power consumption from network synchronization. As the number of channels increase, guard time ecomes smaller and the receiver power starts to become a significant portion of overall power consumption.

A.3 Variable bandwidth allocation scheme

The result of previous analysis gives us basic design methodology for minimizing power consumption of sensors in a fixed cell density and bandwidth. If the network has more than one cell, power consumption can be minimized by optimizing each cell according to its environment(i.e., number of sensors, available bandwidth). However this requires that sensors in different cells to be configured to different specifications (i.e.,channel spacing, noise requirements, etc.). This becomes more significant if the sensor distribution is non-uniform over the network. Unfortunately, the radio modules are not flexible enough to change its configuration accordingly and hence a global MAC layer must be designed for multi-cell network such that all sensors have the same specification.

In this section, we explore how bandwidth allocation can effect the power consumption when there is a large variation in the cell densities. Two scenarios can be considered on how bandwidth is allocated to the cells. First is the conventional fixed bandwidth allocation(FBA) scheme, where each cell is allocated a fixed amount of bandwidth regardless of its density, as shown in Figure 4(b) As opposed to the FBA, we can allocate different amounts of bandwidth to each cell. This is shown Figure 4(a), where available frequency band is divided into smaller frequency slots of signal bandwidth. While FBA scheme assigns equal amount frequency bands to all the cells, variable bandwidth allocation(VBA) scheme allocates frequency slots which is proportional to the number of sensors in a cell. The problem of this approach however, is that some sensors may suffer from co-channel interference if two neighboring cells use same frequency band at the same time. This problem can be solved if time synchronization is maintained across the entire cellular network. We have developed a VBA scheme, where sensors are allocated transmit slots such that guard time is maximized. Simulation result of VBA and CBA is shown in Figure 5, where total average power consumption of the sensors is plotted vs standard deviation of the cell density. It is based on a 25 cell network where each cell has 30 sensors on average and up to 300 sensors. We can see that VBA approach consumes lower power than the FBA scheme as the spatial variation of the network is increased.

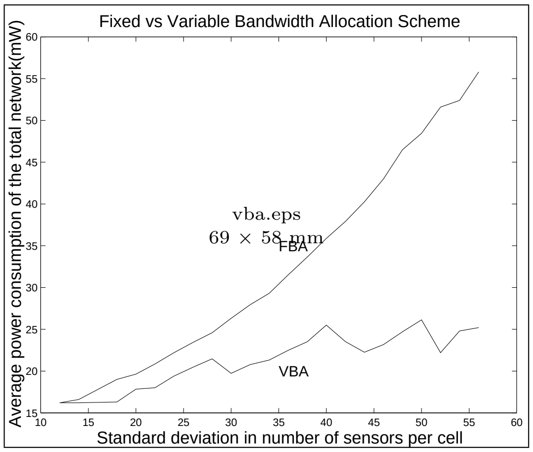

Fig. 5. Power consumption for different frequency allocation schemes

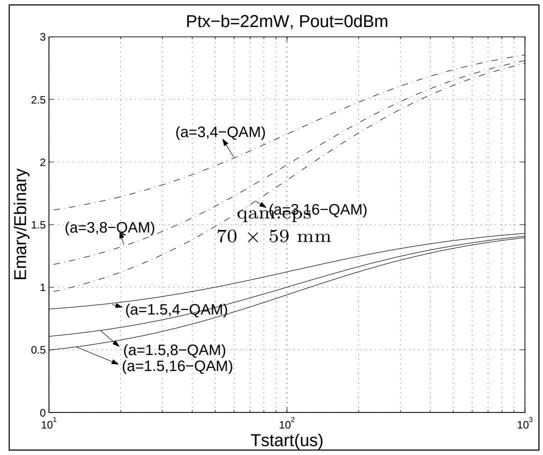

Fig. 6. Energy Saving vs Overhead(α)

The energy saving comes from the fact that guard time can be increased since more bandwidth is available to the cells that have more number of sensors.

B. Modulation

Modulation scheme in physical layer is another important factor which strongly impacts the power consumption. To increase the energy efficiency, it is desirable to reduce the transmit on-time of the radio by sending multiple bits per symbol (i.e. m-ary modulation). The cost, however, is the increased circuit complexity which results in higher power consumption in the modulation circuitry as well as reduced efficiency at the output power amplifier stage.

The energy consumption for binary and m-ary modulation schemes are described in Eq. 4 and 5, where $P_{tx-B/M}$ is the is power consumption of the transmitter, P_{out} is the output transmit power which drives the antenna,T_{on} is the transmit on time, T_{start} is the transmitter start time, n is the number of bits per symbol, α is the ratio of modulation circuitry power between m-ary and binary modulation Basically α is the overhead energy from going to binary to m-ary modulation.

$$E_{bin} = P_{tx-B}(T_{on} + T_{start}) + P_{out-B}T_{on} \tag{4}$$

$$E_{m-ary} \;=\; P_{tx-M}(\frac{T_{on}}{n} + T_{start}) + P_{out-M}\frac{T_{on}}{n} \tag{5}$$

$$\alpha = P_{tx-M}/P_{tx-B} \tag{6}$$

The energy comparison of binary and m-ary case is shown in Figure 6, where energy ratio of m-ary and binary scheme is plotted vs. startup time for different overheads($\alpha = 1.5, 3$). First, we can see that energy is reduced for smaller overhead, α and higher m since the on-time(T_{on}) is shorter. We also notice that the energy savings we get from m-ary modulation depends not only on the overhead but also on startup time. Although m-ary modulation reduces on-time and save energy during active transmission, startup time is a hidden cost which limits the amount of energy savings. It can be seen that for α=1.5, $T_{startup}$ must be less than 40μs in order for the m-ary scheme to achieve lower power than binary case. As α is increased, it becomes more difficult for m-ary scheme to achieve lower energy than binary scheme since $T_{startup}$ becomes more of a dominant factor. We see again that startup transient is again an important factor when choosing low power modulation scheme.

C. Conclusion

Energy efficient protocols for short range, low data rate sensors has been investigated at MAC and physical layer. A variable bandwidth allocation scheme was proposed to reduce the energy consumption for sensor networks which have large spatial variation in sensor distribution. It has also been shown that startup energy can dominate the overall energy consumption of the sensors for short packet sizes. Therefore it is important that this inefficiency is taken into account when communication layers are designed.

D. Acknowledgment

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