Fault Tolerant and Energy-Efficient Real-Time Scheduling of Packet Transmission for Wireless Network Interface Cards

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Abstract

This paper presents a means to reduce power consumption of real-time wireless systems by buffering packets and forcing wireless device to sleep. Optimal power saving strategy satisfying latency and reliability requirements for packet transmssions is derived through mathematical analysis.

1. Introduction

The importance of energy conservation in wireless devices has been emphasized in the literature [2]. Because active state typically consumes ten times more power than sleep state, Cai *et. al.* [1] suggest inserting a buffer between a data producer and its consumer to queue data while the data consuming device is placed into a sleep state. In reality, the power conservation should, however, be considered along with reliability and latency requirements of transmission. This paper extends [1] by considering systems with these requirements.

2. System Model

We will consider a system model shown in Figure 1 that a buffer is inserted between a packet generator and a wireless network interface card (W-NIC). This is the sender side of a point-to-point communication. Packet arrivals are modeled as Poisson random process with parameter λ and the W-NIC can be turned off while packets are being accumulated in the buffer in order to reduce power consumption. When the number of buffered packets reaches N_p, the sleeping W-NIC is woken up by the main processor and it sends the buffered packets as a stream. The stream uses a channel coding scheme with at most N_r number of retransmissions on failure of the transmission. Data sink is assumed always ready to receive the stream. Once the system receives one acknowledgement (ACK) for the entire stream from the data sink, it goes again to sleep mode.

Here, how much power the system can save due to the buffering and sleeping depends among others on the two parameters: N_p and N_r. The objective of this paper is to find the optimal values of these two parameters for minimizing the expected power consumption per packet, satisfying an expected maximum packet delay constraint and guaranteeing a minimum transmission reliability.

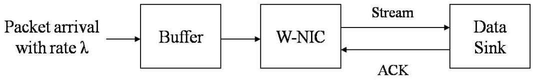


Figure 1. System model.

3. Problem Formulation

In the model above, the system will operate as shown in Figure 2. Every time the number of packets in the buffer is equal to N_p, the system begins to transmit the buffered packets as a single stream. Thus the maximum delay due to buffering is equal to the delay that the first packet of the stream experiences in the buffer until the N_p-th packet arrives. Since interarrival time of the Poisson process follows Exponential distribution with mean $1/\lambda$, the expected maximum delay $D(N_p, N_r)$ can be written as follows:

$$D(N_p, N_r) = \frac{N_p - 1}{\lambda} + d(N_p, N_r), \tag{1}$$

where $d(N_p, N_r)$ is the expected delay due to transmission and retransmission expressed as

$$d(N_p, N_r) = N_p t_s + E(N_f)(N_p t_s + t_r), \tag{2}$$

in which t_s denotes the time to send a packet, t_r is the time for recovery to begin retransmission, and N_f represents the number of failures that each stream may suffer. Delay due to retransmission is the timeout, after which retransmission

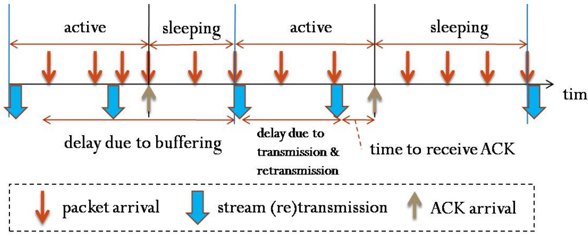


Figure 2. Operation example with $N_p = 6$.

occurs. Given N_r and stream error rate E_s, the expected value for the N_f is obtained as

$$\begin{aligned} E(N_f) &= \sum_{k=0}^{N_r-1} kE_s^k(1-E_s) + N_r E_s^{N_r} \\ &= \frac{E_s(1-E_s^{N_r})}{1-E_s}. \end{aligned} \tag{3}$$

Note that if the stream is still in error after the last trial of retransmission, it is dropped. Here E_s is assumed to decrease as the length of stream increases, which is because any channel coding scheme except convolutional code results in better performance as the stream legngth increases, given the coding rate is kept constant. On the other hand, since the number of retransmissions basically follows Geometric distribution with parameter E_s, the reliability of the stream transmission $R(N_p, N_r)$ is

$$R(N_p, N_r) = 1 - E_s^{N_r+1}. \tag{4}$$

Now from (2), if the system consumes power at rates P_{active} while active and P_{sleep} during sleeping, we can derive the expected power $P(N_p, N_r)$ consumed to transmit a stream as follows:

$$\begin{aligned} P(N_p, N_r) &= N_p P_t(E(N_f)+1) + P_r \\ &+ \left(d(N_p, N_r) + t_{ACK}\right) P_{active} \\ &+ \left(\frac{N_p}{\lambda} - d(N_p, N_r) - t_{ACK}\right) P_{sleep}, \end{aligned} \tag{5}$$

where P_t and P_r denotes the power comsumption per packet when sending a stream and the power consumed to receive the ACK, respectively, and t_{ACK} is time required to get the ACK.

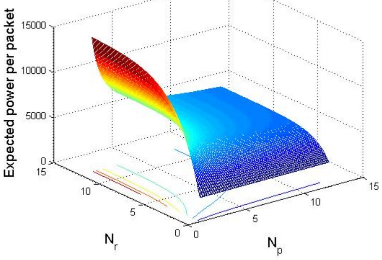
Using (1), (4), and (6), the optimal values for N_p and N_r are obtained by solving the following optimization problem:

$$\min_{N_p, N_r} P(N_p, N_r)/N_p \tag{6}$$

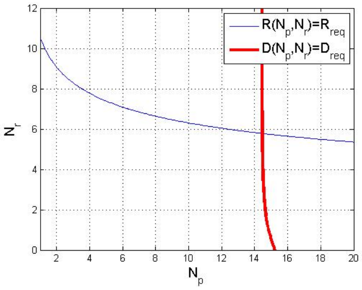
subject to the constraints such that $D(N_p, N_r) \leq D_{req}$ and $R(N_p, N_r) \geq R_{req}$, where D_{req} and R_{req} are thresholds required for delay and reliability, respectively.

4. An Example of the Optimum Solution

We select Compaq WL110 W-NIC that has its power parameters as P_t = 391mW, P_r = 141mW, P_{active} = 407mW, and P_{sleep} = 38mW, and solve the problem in (6) modeling the stream error rate as a Weibull distribution $E_S = e^{-(\lambda_f N_p)^\alpha}$ where $\lambda_f = 0.01$ and $\alpha = 0.2$. Using a well known constraint optimization technique, Karush-Kuhn-Tucker condition, we found that the optimal solution, if exists, is the point that simultaneously satisfies the two contrainsts with equality. As an example, fixing other parameters as D_{req} = 1.5ms, R_{req} = 0.99, t_s = 5μs, t_r = 10μs, $t_{ACK} = t_s$, and λ = 10kHz, we have $(N_p, N_r) = (14.4, 5.8)$ as the optimal solution when relaxing the each element of (N_p, N_r) a real value.



(a) Expected power per packet for given N_r and N_p.



(b) Feasible region given at upper left of the plane partitioned by the two-constraint curves.

Figure 3. Power per packet and feasible region.

We can see that this is indeed true from the Figure 3 that shows the expected power per packet and feasible region for the solution. In Figure 3(b), the region to the top left bounded by the two curves satisfies the delay and the reliability requirements and therefore defines the feasible solution region. Feasible integer solution, our ultimate goal, comes by mapping the point to the nearest feasible point in this case, that is, $(N_p, N_r) = (14, 6)$.

5. Conclusion and Future Work

We have presented a real-time scheduling method for packet transmission that can maximaly save power consumption given latency and reliability constraints. We plan to continue this work by simulation study that considers different stream reliability models, other than perfect synchronization between sender and receiver.

References

[1] L. Cai and Y.-H. Lu. Dynamic Power Management Using Data Buffers. In *DATE '04*, 2004.

[2] Q. Qiu, Q. Wu, and M. Pedram. Dynamic Power Management in a Mobile Multimedia System with Guaranteed Quality-of-Service. In *Design Automation Conference*, 2001.