A TRANSMISSION RATE AND ENERGY DESIGN FOR POWER AWARE LOCALIZATION IN AD HOC AND SENSOR NETWORKS

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ABSTRACT

In this paper we consider a signal strength based location-aware network and evaluate how to optimize energy consumption while achieving a certain accuracy in the localization result. Obviously, the greater the accuracy, the greater energy will be consumed, and, although different strategies can yield similar localization accuracy, their energy efficiency can be different. The relationship between these parameters is evaluated and the optimum strategy is found with respect to the transmission power of the packets, the packet transmission rate, the signal to noise ratio at the receiver and the packet reception rate. From this analysis, some guidelines for the efficient management of energy for localization in an ad hoc or sensor network are extracted.

I. INTRODUCTION

Wireless sensor and ad hoc networks have interesting advantages such as rapid deployment, robustness, flexibility and inherent support for mobility. But, on the other hand, they present a number of technical challenges [1-4] that differ from traditional wireless systems and wired networks, in terms of reliability, power resources, storage and computing capacity, network management, etc. Among these issues, energy management at each node and in the global net as a whole is a key point, since wireless devices depend on limited energy resources (batteries). This has promoted a strong line of research on efficient energy saving protocols [5].

It should be noticed that the radio system is the most energy demanding part of a node. Therefore, in order to reduce energy consumption, any sensor or ad hoc network should minimize the percentage of time that nodes are transmitting or receiving.

On the other hand, automatic localization of the nodes in a sensor or ad hoc network is a key enabling technology [6]. The location information may be essential to interpret the gathered data. In addition, location information can be used to optimize some network aspects, for example, for power aware and scalable (geographic) routing algorithms [7, 8].

Several location techniques have been proposed for wireless networks [9, 10], such as GPS, RF, ultrasounds or infrared devices. Among them, RF-based location techniques [11] are really appropriate for the use in ad hoc and sensor networks, since, besides the radio system, no additional costly and power-consuming hardware is needed.

RF-based techniques consist of measuring certain parameters of the radio signal that one node receives from another node, such as the angle of arrival (AOA), the time of arrival (TOA) or the received signal strength (RSS) [12 - 14]. RF-based accurate localization is still a challenge, especially indoors, due to the effects of shadowing, multipath and fading on the RF signal.

In this paper we analyze the energy consumption in the transmitter nodes of a RSS-based localization network and we extract some guidelines for the efficient management of energy when developing a localization technique in a sensor or ad hoc network. With the evaluation of the energy consumption in a representative case, we find the strategy, in terms of transmission power and time scheduling that, ensuring a given average number of received packets (needed to have a certain desired accuracy in the RSS measurements), gives the lowest consumed energy. Although we illustrate the results of the analysis for a particular channel and communications model, the method is directly extensible to other models.

The rest of the paper is organized as follows. Section II states the problem and describes the communication scheme on which our localization mechanism is based. In Section III the channel models that have been selected for our analysis are briefly described. The experiments that were carried out with Crossbow's MICAz motes to check the suitability of these models and their results are also presented. Section IV analyzes the energy consumption of the localization procedure. The optimum strategy is found with respect to the transmission power of the packets, the packet transmission rate, the signal to noise ratio at the receiver and the packet reception rate. Some examples are also presented for the particular case of our wireless sensor network and channel models. Finally, Section V extracts some conclusions of the analysis and sketches some applications of the obtained results.

II. PROBLEM STATEMENT

Let us consider a sensor network in which the location of the nodes is based on RSS measurements.

As nodes in the network can move, the localization must be performed periodically, and thus, the nodes will have to transmit localization packets periodically.

When a node receives a packet from another node, it measures its RSS. This measure can be used to estimate the distance from the sender of the packet by comparing it to the transmit power or by any other method based on fingerprinting. We accept that the accuracy of the localization depends on the accuracy of the RSS measurement. In order to obtain an accurate value of the RSS it is necessary to average the RSS of several packets (let's say n, for a given desired accuracy). When a higher accuracy is needed, a higher number of packets should be averaged.

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The objective is to find the transmission strategy that achieves the desired accuracy in the averaged value of the RSS, with a minimum consumed energy.

Although only the transmission energy will be considered for the analysis, it applies for the total consumed energy in the real network, since the consumed energy in the receiver will be proportional to the consumed energy in the transmitter.

Let us suppose that a node will average the RSS of all packets received during a period of time T_0, which depends on how often the localization of the node must be performed. If every transmitted packet arrived to the receiver, the transmitter node would only have to send n packets during T_0, so that the receiver would average their RSS to obtain the desired accurate value. But, obviously, in radio communications there is no guarantee that all the transmitted packets are received. A node will receive the transmitted packets with a given probability: the packet reception probability (*PRP*) or packet reception rate, which is a function of the signal to noise ratio (*SNR*), (see section III). Therefore, in order to receive n packets during T_0, packets can be sent either with a high transmission power (so that the *SNR* is high and very few transmitted packets are lost) at a rate of n/T_0, or with a lower power (some packets will be lost) but at a higher rate (k/T_0, with $k>n$). The objective is to find the rate which involves the lowest global energy consumption.

The transmission strategy is defined by two parameters: the transmit power (P_{TX}) and the time between transmitted packets (T), that is, the inverse of the packet transmission rate (k/T_0). We also admit the possibility of retransmitting a packet (a maximum of M times, including the first transmission) if it is not received. For this, we assume that the sender knows if the packet has been received, i.e., that the ACK packets are never lost. Fig. 1 shows an example of transmitted and received packets, with k=4, n=3 and M=2.

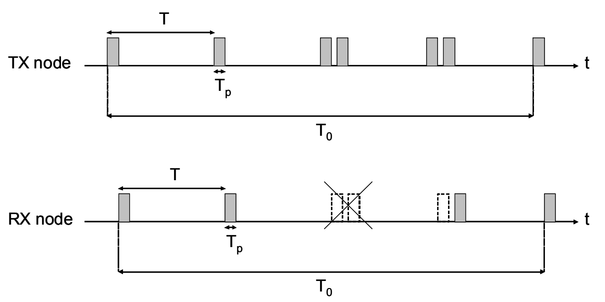

Figure 1 : Diagram of the transmitted and received packets. In this example the number of transmitted packets during T_0 is k=4. The third packet is not received the first time it is transmitted, so it is retransmitted, but not received again. As M=2, the packet is not retransmitted a third time, and the packet is lost. The fourth packet is not received the first time, so it is retransmitted. In this case it is received. The final number of received packets is n=3.

III. Channel Models

In order to evaluate the energy consumption during the localization procedure, some assumptions about the receiver and radio channel behavior must be done. First, the relation between the *PRP* and the *SNR* at the receiver must be established. And second, an attenuation model of the channel (that is, the variation of the received signal strength with the distance) must be also assumed.

In the following we propose to use simple models of the receiver and the channel and we validate them experimentally for our hardware. By no means have we intended to justify their suitability in any environment, but only to check that they approximately reflect the behavior of our wireless network.

A. PRP-SNR relation

If it is assumed that there is no error correction, a packet will be received correctly only if all its bits are received correctly. On the other hand, it is well known that the probability of bit error, or bit error rate, depends on the encoding and modulation of the radio signal, therefore, the *PRP* will also depend on them. For example, for QPSK and BPSK modulation schemes [15], the probability of a successful reception of a packet of length l, in presence of additive white gaussian noise and in absence of interferers, is given by:

$$PRP = (1 - BER)^{8 \cdot l} = \left(1 - Q\left(\sqrt{2\frac{E_b}{N_0}}\right)\right)^{8 \cdot l}, \quad (1)$$

where E_b is the energy per bit, $N_0/2$ is the two-sided power spectral density of the noise and E_b/N_0 is the signal to noise ratio (from now on *SNR*).

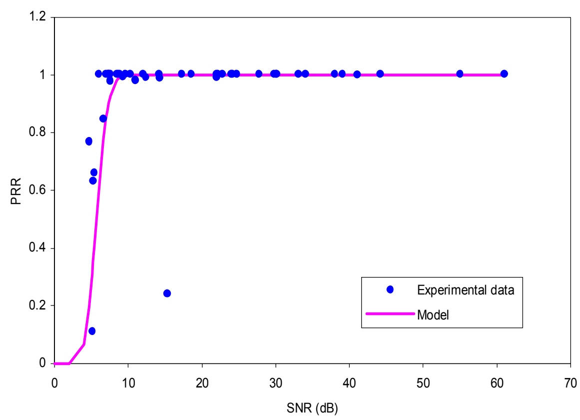

Figure 2 : Relation between *PRP* and *SNR*. The *PRP* of the experimental data was obtained from the ratio between the number of received packets and the number of transmitted packets in each experiment. The *SNR* was calculated from the averaged RSS of the packets as *SNR* = RSS – *N*, where *N* is the theoretical noise level.

In order to see if this model was reasonably valid for our hardware, some simple experiments were made with our Crossbow's MICAz motes. The MICAz is a 2.4 GHz node with direct sequence spread spectrum radio which uses an O-QPSK modulation scheme. Two motes were used for the experiments, one as transmitter and one as receiver connected to a computer. The experiments were carried out in a controlled electromagnetic environment in which there were no interfering signals. In each experiment, the transmitter node transmitted a packet of 27 bytes every second and the receiver node measured the RSS of the received packets. The experiment was repeated for different distances between transmitter and receiver and for different transmission powers in order to have different values of *SNR* at the receiver. The experimental results are shown in Fig. 2, together with the theoretical model given by (1). As it can be noticed, the experimental data adjust quite well to the model, with the exception of some outliers.

B. *Path loss model*

On the other hand, a model of the channel that relates the transmitted power to the receiver power is also needed, as it will provide a relation between transmitted power (P_{TX}), *SNR* at the receiver and distance (d) between transmitter and receiver. One of the simplest propagation loss model is the log-normal shadowing path loss model [16]:

$$L(dB) = L_0(dB) + 10\eta \log \frac{d}{d_0} + X(dB) , \tag{2}$$

where L_0 is the power loss for a reference distance d_0, η is the path loss exponent and X is a zero-mean Gaussian with standard deviation σ.

We also made some experiments to characterize our radio channel. In these experiments, two MICAz motes were used again, with the same configuration that in the *PRP* experiments. The RSS of the received packets was measured for different distances between transmitter and receiver and for two different transmission powers (0 dBm and -10 dBm). At each position, several measures of RSS were obtained, in order to average their values. The experimental results are shown in Fig. 3.

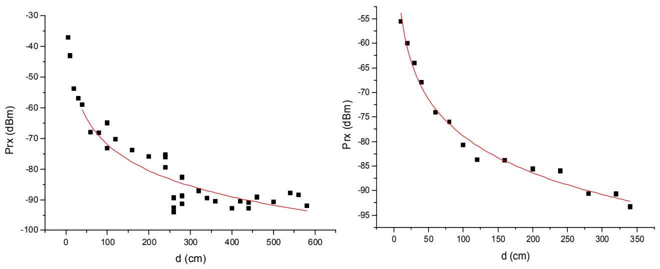

Figure 3 : Received power vs. distance for a transmission power of 0 dBm (left) and -10 dBm (right). The received power of each point was calculated by averaging a series of RSS measures.

The solid line in both figures represents the fitting of the experimental data to the curve:

$$P_{RX}(dBm) = P_{TX}(dBm) + A - 10\eta \log \frac{d}{d_0} , \tag{3}$$

where A is a constant term. From the curve fitting in Fig. 3, a value for the path loss exponent was obtained: $\eta = 2.8$ for the curve with a transmission power of 0 dBm and $\eta = 2.5$ for -10 dBm.

As previously said, this channel model provides a relation between the transmitted power (P_{TX}), the *SNR* at the receiver and the distance (d) between transmitter and receiver, i.e.:

$$SNR(dB) = P_{TX}(dBm) + A - 10\eta \log \frac{d}{d_0} - N(dBm) , \tag{4}$$

where N is the noise level at the receiver.

IV. Analysis of the Power Balance

This section evaluates the power consumption in a wireless network like the one described in section II. First, we perform a general analysis in terms of the communication strategy parameters. Finally, some results are presented for the particular case of our wireless sensor network.

A. *General analysis*

Let's first calculate the relationship between the transmission power (P_{TX}) and the time between transmitted packets (T) for a given accuracy. The random uncertainty when averaging n measurements of RSS can be expressed as [17]:

$$\Delta RSS = t_{n-1} \frac{\sigma_{n-1}}{\sqrt{n}} , \tag{5}$$

where σ_{n-1} is the standard deviation of the data and t_{n-1} the value of the Student t distribution for a confidence level of α and n-1 degrees of freedom. So, a desired accuracy imposes a minimum number of received packets.

On the other hand, the probability of losing all the transmissions (M) of a packet is $(1\text{-}PRP)^M$. Thus, the average number of packets that are finally received, when k packets are transmitted, is:

$$n = k - k \cdot (1 - PRP)^M = \frac{T_0}{T} \cdot \left(1 - (1 - PRP)^M\right). \tag{6}$$

Consequently, a desired accuracy in the RSS imposes a relationship between T and *PRP*, given T_0 and M. As the *PRP* depends on the *SNR* at the receiver, and the *SNR* is proportional to the transmit power P_{TX} for a given distance d between transmitter and receiver, as shown in section III, there is a relationship between P_{TX} and T for a given desired accuracy. Among all *PRP*-*T* (or P_{TX}-T) pairs that ensure the required number of received packets, we want to find the one with the lowest energy consumption.

Let's now calculate the consumed energy during the period T_0 in terms of the design parameters. Note that, since the localization procedure is periodic (with period T_0), the consumed energy during this period is an appropriate parameter to analyze the power efficiency.

During this period of time, k packets are transmitted; thus the consumed energy is $P = k{\cdot}E/T_0 = E/T$, where E is the consumed energy when transmitting a single packet (and its possible retransmissions). If there were no retransmissions (or M=1), the consumed energy would be $E = P_{TX}{\cdot}T_p$, where T_p is the packet length. But if M>1, the consumed energy will, in average, increase:

$$E = P_{TX} \cdot T_p \cdot \left(1 + \sum_{i=1}^{M-1} (1 - PRP)^i\right) = P_{TX} \cdot T_p \cdot \frac{1 - (1 - PRP)^M}{PRP} . \tag{7}$$

As it is expected, the consumed energy increases with the transmission power and the maximum number of transmissions and decreases with the *PRP* (the higher the *PRP*, the fewer packets will be lost and the fewer retransmission will be needed).

On the other hand, the time T between series of packets can be obtained from (6). Finally, we obtain the consumed energy during the period T_0:

$$P = \frac{E}{T} = \frac{P_{TX} \cdot T_p \cdot n}{T_0 \cdot PRP}, \qquad (8)$$

where n is the average number of received packets.

It can be noticed that the consumed energy does not depend on the maximum number of transmissions (M). When M increases, the consumed energy (E) increases as well, but so does the time between packets (T). Both contributions are cancelled. To intuitively understand this result, it should be remembered that n has a given fixed value, determined by the desired accuracy.

B. *Results*

All the figures presented in this section are calculated using the parameters of our sensor network, which performs a localization once a second, that is, T_0 = 1s, and uses 27 bytes-packets, with T_p = 864 µs.

In Fig. 4 the relation between the consumed energy and the *SNR* at the receiver is plotted for different values of desired accuracy (ΔRSS, in dB units) and for any value of M, since the consumed energy does not depend on the value of M, as mentioned above. The consumed energy was calculated as a function of the *SNR* using (8), obtaining n from (5), P_{TX} from (4) and *PRP* from (1). From the experiments described in section III we obtained that the value of σ_{n-1} is around 1dB. We could use this value in (5) together with an appropriate value of t_{n-1}, but, as this values are only scale factors that do not affect the outline of the curve, we have considered $t_{n-1} \cdot \sigma_{n-1}$=1, without loss of generality for our purposes.

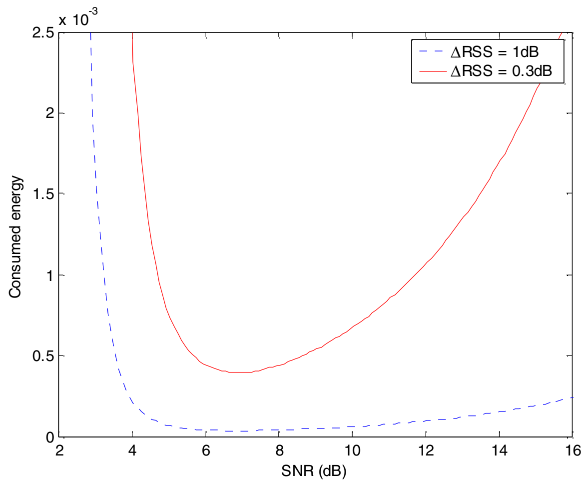

Figure 4 : Relation between consumed energy and *SNR* at the receiver for any value of *M*. Two curves are shown, each one corresponding to a different accuracy. All the points in each curve give the desired accuracy.

Obviously, the greater the required accuracy, the greater energy will be consumed. Each point in Fig. 4 corresponds to a different value of *SNR* and, thus, to a different value of T. It can be noticed that there is an optimum value of the *SNR* in terms of consumed energy. Furthermore, this value (approximately 7dB in the figure) does not depend on the desired accuracy. It can also be seen that the relation between energy and *SNR* does not depend on the value of M. Taking a look at (8) we can see that the optimum value of *SNR* only depends on the *PRP*. Fig. 2 showed the theoretical relation between *SNR* and *PRP*. It can be noticed that the region where the energy consumption is small (5 < *SNR* < 10, approximately), is the transitional region between *PRP* = 0 and *PRP* = 1. The minimum energy point (*SNR* = 7 dB) corresponds to a *PRP* of 0.85 approximately.

As a result, if we want to measure the RSS with certain accuracy, the best transmission strategy is to transmit packets with a transmission power such that the *SNR* at the receiver is the optimum. If the optimum value is not achievable, we conclude from Fig. 4 that it is better to use a higher transmission power, as the increase of power consumption with the *SNR* is lower for higher values of *SNR*.

In Fig. 5 the relation between the consumed power and the time between transmitted packets T at the receiver is plotted for different values of M and desired accuracy.

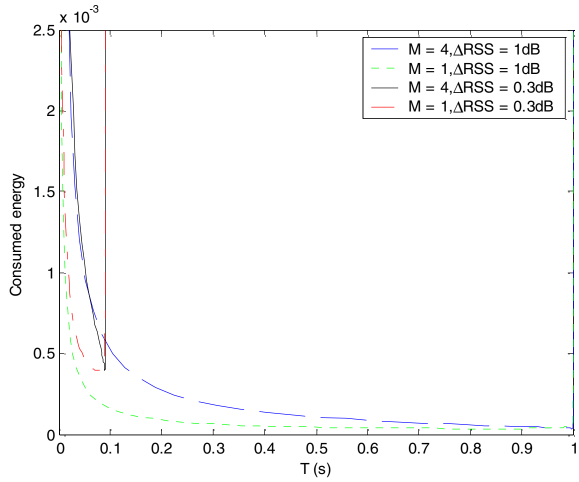

Figure 5 : Relation between consumed energy and *T* for two different values of desired accuracy and two different values of *M*. All the points in each curve give the desired accuracy.

Each point in Fig. 5 has a different value of T and, thus, a different value of *SNR*. It can be noticed that there is an optimum value of T in terms of consumed energy. Furthermore, this value is different depending on the desired accuracy and the maximum number of transmissions of a packet (M). If the desired accuracy increases, the time between transmitted packets should be smaller, as more packets should be averaged at the receiver. If M increases, the time between transmitted packets does not need to be so high, since the probability of receiving a packet increases.

As a result, if we want to measure the RSS with a certain accuracy, the best transmission strategy is to transmit packets with a packet rate of $1/T^*$, with T^* the optimum time between packets for the desired accuracy and M. If the optimum value is not achievable, it is better to transmit with a higher packet rate (a lower T), as the increase of energy consumption with T is lower for lower values of T.

C. Remarks

In conclusion, among the pairs SNR-T that satisfy a desired accuracy for a given M, there is a pair SNR^*-T^* for which the energy consumption is minimum. Therefore, the best transmission strategy consists on transmitting packets with a packet rate of $1/T^*$ and such a transmission power that the SNR at the receiver is equal to SNR^*.

As pointed out in section III, the SNR at the receiver depends on the transmission power (P_{TX}), but also on the distance (d) between transmitter and receiver. Hence, in order to achieve the desired SNR at the receiver, we have to take the two parameters into account.

For instance, we could adaptively modify the transmission power (P_{TX}), estimating the value necessary to achieve the desired SNR at the receiver. In this case, an estimate of the distance d between transmitter and receiver would be needed in order to calculate the transmission power from (4).

As an example, Fig. 6 shows the relation between the consumed energy and the P_{TX} for a distance d = 2 m and for different values of desired accuracy. If this were the case, the lowest power consumption would be achieved by choosing a transmission power of -14.5 dBm.

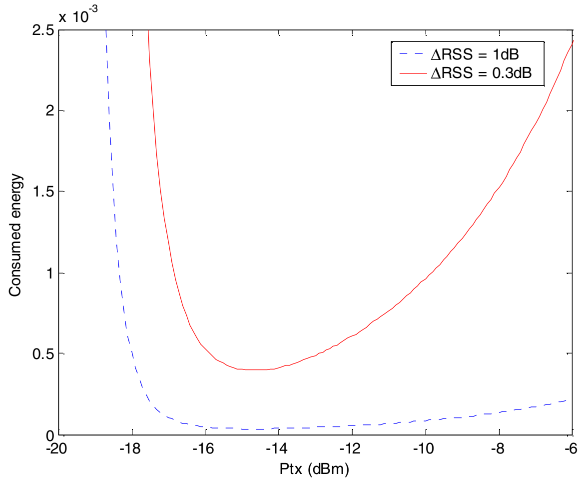

Figure 6 : Relation between consumed energy and transmission power for a distance between transmitter and receiver of 2 m, for any value of M. Two curves are shown, each one corresponding to a different accuracy. All the points in each curve give the desired accuracy.

V. Conclusions and Further Work

In this paper we have presented an analysis of the consumed energy in a signal strength based location-aware wireless network and we have optimized the energy consumption and time scheduling.

It should be noted that, although we have assumed for the analysis that the objective is to obtain a certain accuracy in the RSS for the localization of the nodes in the network, the analysis and its results are also valid for any procedure that requires to have a certain number of average received packets during a given time interval.

If the distance between transmitter and receiver is known, the transmission power could be estimated from (4). If the distance between transmitter and receiver is unknown, the results above can still be used with the help of a power control loop. In this case, the transmission power would have to be estimated iteratively.

The obtained results can be used in a number of ways in sensor and ad hoc networks. Some of the applications include, besides efficient localization, energy-efficient routing algorithms and power control.

Further work would include the analysis of other channel and receiver models and the evaluation of variant channels. Some experimental tests could also be carried out in order to measure the consumed energy in real sensor networks when using the optimal strategy obtained in this paper in comparison to other strategies.

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