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Lynggaard , P.; Blaszczyk, Tomasz

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An Energy-Efficient Link with Adaptive Transmit Power Control for Long Range Networks

P. Lynggaard
CMI, Aalborg University Copenhagen
Copenhagen, Denmark
perlyn@es.aau.dk

T. Blaszczyk
CWSA, DTU Diplom
Technical University of Denmark
Ballerup, Denmark
tomb@dtu.dk

Abstract — **A considerable amount of research is carried out to develop a reliable smart sensor system with high energy efficiency for battery operated wireless IoT devices in the agriculture sector. However, only a limited amount of research has covered automatic transmission power adjustment schemes and algorithms which are essential for deployment of wireless IoT nodes. This paper presents an adaptive link algorithm for farm applications with emphasis on power adjustment for long range communication networks.**

Keywords—IoT; WSN; energy saving; transmission power adjustment; adaptive wireless links; solar power in WSN

I. Introduction

The demand for smart sensor system based IoT devices in the agriculture sector is huge. Especially, IoT devices for plant and crop protection which monitors diseases, insects-attacks, and extreme weather anomalies are in focus. To deal with these challenges the IoT devices have autonomous computational capability and are able to communicate with a cloud system for reporting and offloading data in an energy efficient manner. Thus, saving energy is one of the key challenges in these systems [1]. In this paper we focus on energy management in a distributed wireless sensor system for agriculture usage. Energy management is needed to deal with the challenges of limited power (battery rechargeable units) and long communication distances between the nodes, i.e. it has impact on the application usability, reliability, and the life time of overall network. We present an algorithm and simulate its behaviour in the light of energy savings, message propagation time, message size, and dynamic behaviour.

As an alternative to using maximum available transmission power for each sensor node it should adjust its transmission power to the needed level for achieving a reliable communication channel regardless of weather conditions, obstacles, dynamic distance variation, manmade noise and other disturbances. The presented energy efficient adaptive link model provides an adaptive transmission power algorithm which uses interaction between the sensor nodes in order to determine the transmission power. The algorithm can be deployed in static networks as well as in dynamic ad-hoc networks.

II. Related Works

In our recent work [1] we have presented an adaptive link model based on message propagation between the nodes. It presents an algorithm that is able to adapt to weather conditions, available power, and time of day/night for a sustainable and energy limited system based on solar cells. This work uses the CC1120 hardware RF modules and it assumes that the sensor nodes do not have dynamic transmit output power adjustment. However, for fast deployment and limited configuration and maintenance efforts it is strongly desirable to rely on “automatic” transmission power adjustment to set the proper link margin and run the nodes at their optimal transmission power. Depending on the topology and the communication distance an automatic transmission power adjustment approach can save a lot of energy in battery operated devices.

A large proportion of the IoT devices on the market do not have automatic transmission power adjustment. However, new devices such as the SIGFOX GPS network tracker [2] offers a possibility to implement such algorithms, but its defaults the transmit power to a constant value (maximum power) [3]. A lot of research is ongoing to find efficient algorithms for adaptive links which regulate the transmit power in terms of energy savings. One example is the work performed by Chen et al. [4] which proposes method to minimize energy in communication network by reducing overall sensor transmission power. Their algorithm uses an approach based on constructing a Relative Neighbourhood Graph and optimizes the performance in relation to this. Nonetheless, their algorithm focuses on cluster of nodes whereas this work presents an algorithm which is capable of handling node to node communication as well.

III. The Concept and the Challenges

The context for this work is limited to devices distributed in farm fields and forests. Due to large distance and lack of power resources in this context the IoT nodes must operate on ambient energy sources such as photovoltaic cells, mechanical harvesting, etc).

There is plenty of use-case scenarios in the farm-domains where IoT sensors solve problems in cost effective manner, e.g. scenarios which cover disease control for plant and crop protection as presented in paper [1]. One of these scenarios is presented in the next section.

A. A case study of bee family condition in modern beehives

The map presented on Fig. 1 shows beehives placed in 2 spots in distance of 600m and 1.1 km away from farmhouse shown in left bottom corner. Additionally close to one beespot there is weather station.

Fig. 1. . A farm equipped with IoT devices for tracking bee family condition

For a bee family to grow up after a winter period, it is important to provide the right air conditions inside the beehive. Modern beehives are constructed with light styrofoam material which has many beneficial properties such as low thermal conductivity, low weight, and low size. Nevertheless, this type of construction requires frequent inspections to ensure that the air exchange between the interior and the external environment is sufficient to control the moisture level inside the beehive. One method that deals with this challenge regulates the ventilation valve and at the same time monitoring the temperature loss [5]. Improper control of temperature and humidity in the context of changing weather condition might lead to large food consumption and it can have fatal consequences for a bee family.

Currently bee-families are monitored by manual inspection which is costly and cumbersome. Such systems can easily be automated and implemented by using smart sensor devices to monitor humidity, temperature.

B. Radio and sensor hardware choices

In order to relate the simulation model used in this paper to the real world settings we have used the parameters from selected HW modules (as presented on Fig. 2) as input for the simulations. The RF modules used in this work provide a transmit power range of: -11,-6,-3,0,1,2,3,4,5,6,7,8,9,10,11,12 ,13,14,15,27 dBm. These output power settings as a function of input power are presented in Fig 2.

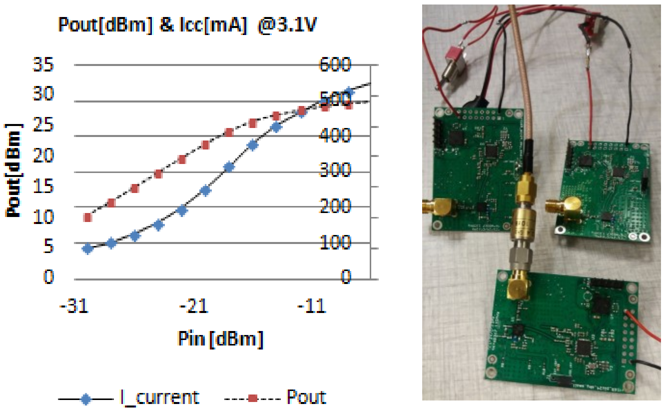

Fig. 2. Current consumption @3.1V for RF169MHz module with PA activated (leftmost) Hardware RF modules based on the wireless CC1125 device (rightmost).

C. An adaptive power control algorithm

The presented algorithm has been designed and tested in a farm application where a weather station sends data over a RF link to a gateway (every 10 minutes) which collects the data and uploading these to a Cloud, Fig. 4.

The basic algorithm flowchart is presented in Fig. 3. This algorithm will be invoked every time a package is sent.

```
This algorithm can run on RF1 or RF2 (*RF2).
(*RF2) - for algorithm running on RF2.

1. Power up IoT node RF1 (*RF2)
2. Initializing values:
L=0
R=19 // sizeof(T)-1
T[] = {-11,-6,-3,0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,27} // array of dBm
values

3. If L<(R-1) is true then:
middle=round(L+R-1)/2
tx_power= T[middle]

4. Packet will be send with output power tx_power = T[middle] from
RF1(*RF2).

4.1 If RF1(*RF2) received confirmation packet from RF2(*RF1) so:
if (send == confirmation) is true then:
last_good_power=tx_power
R=middle

4.2 Otherwise, when RF1(*RF2) did not received confirmation packet from
RF2(*RF1) so:
 if (send == confirmation) is false then:
 L=middle

4.2.1 When RF1(*RF2) did not received confirmation packet from RF2(*RF1)
and if (R==L && R<sizeof(T)-1) is true then:
  R=R+1;
  middle=R;
  L=R;
  txPower=T[middle]

5. Transmit output power is set again -> jump to point 3.

Before next packet is sent, again transmitted output power is calculated
(from point 3).
If condition if(L<(R-1) will be false and condition if(send==confirmation)
will be true so if RF1(*RF2) received confirmation packet from RF2(*RF1),
then minimum output power will be set.
last_good_power will be lowest transmit power step where RF2(*RF1) is
sending confirmation.
```

Fig. 3.Algorithm steps for RF Firmware modules (RF1 and RF2)

Fig. 4. Automatic Weather Station with RF1 module inside

This algorithm is implemented in simulation model for energy efficient adaptive power link analysis in next sections.

IV. AN ENERGY EFFICIENT ADAPTIVE WIRELESS LINK

The key factors for overcoming the challenges of creating an energy efficient link between the receiver and a transmitter discussed previously means dealing with the path loss and the noise sources in the link. To control these is tricky and complex because they vary as a function of time. Examples are: antenna position and polarization are changed by the wind; atmospheric losses changes with rain etc.; adjacent and co-channel interferences increase the receiver noise floor; and new object can arrive in the first Fresnel zone. However, some of these challenges have more impact on the link losses that other, thus the ones with the highest impact are explored and elaborated in the following sections.

A. Path loss

The free space loss is one of the most significant contributions to a wireless link loss. It accounts for the spreading of the transmitted energy as a function of distance. A commonly known formula which covers this is the Friis transmission formula (1).

$$\frac{P_r}{P_t} = G_r G_t \left(\frac{\lambda}{4\pi R} \right)^2 \tag{1}$$

Where: Pr and Pt are the received and the transmitted power respectively. Gr and Gt are the antenna gain for the receiver and the transmitter. λ is the wavelength and R is the distance between the receiver and the transmitter.

As discussed the path loss is a key contributor to the link loss. Thus, the path loss can be as large as 100 dB if the distance between the receiver and the transmitter is 10 km. An additional loss is the loss provided by objects that blocks the line-of-sight (LOS) between the transmitter and the receiver. Especially when an object is partly blocking the first Fresnel-zone has a considerably impact on the path loss [6].

Another key loss factor is the white Gaussian noise sources, which is random processes that occurs in the nature such as thermal vibration from atoms in conductors, black body radiation, etc. In addition to these are the manmade noise sources such as noise from electrical equipments and spill-over from other radio sources placed in the same frequency range. These noise sources can be modelled by using an Additive White Gaussian Channel (AWGN channel) model which adds Gaussian noise power with a constant spectral density [6].

B. A simulation model

To proof link stability in different environments scenarios for the suggested adaptive power algorithm behaviour has been derived and simulated. This simulation model relates to real world settings by in-cooperating parameters from the previously discussed radio-hardware. This concept allows for experimenting and fine-tuning the model parameters to explore and evaluate the pros and cons of the proposed adaptive power algorithm.

The model consists of two parts, where the first part (model-1) is a model that is based on the equations discussed earlier in this paper. It calculates the signal to noise ratio (SNR) at the receiver end based on the parameters in table I and table II. The second model (model-2) simulates the bit-errors in a sequence of transmitted frames, which are transferred through an AWGN channel that incorporates the SNR from the model-1.

TABLE I.

Parameter	***Value***
Distance from the field to the farmer house	10 km
Height (over ground) of farm house antenna	3 m
Height of the antenna - the field IoT device	1 m
Attenuation of object in first Fresnel zone	20 dB
Antenna gain (Rx+Tx)	0 dB

TABLE II.

Parameter	***Value***
Operating frequency	169 MHz
Sensitivity	-120dBm @ 1200 bps, BER=10E-2
Modulation	2-FSK
Radio consumed power RX	69 mW
Radio consumed power TX	150 mW
Microcontroller consumed power	3 mW
PA efficiency	50 %

In general, the simulations assume that the ZigBee wireless transmission protocol is used and that some power saving can be achieved by the radio-interface [7]. The ZigBee protocol uses frames with an overhead of 31 bytes and a maximum payload of 127 bytes. Regarding the radio-interface power savings it is assumed that the microcontroller provides a power saving mode (sleep mode) when no traffic takes place and it is assumed that the sensors have a very low power-consumption (it can be ignored).

The second model (model-2) simulates bit-errors in a sequence of transmitted ZigBee frames. Basically, 2-FSK modulates a short ZigBee frame which only contains one acknowledge token. This frame is piped through an AWGN channel which has a SNR in the range of 0 to 20 dB. Finally, the frame is demodulated and compared to the modulated frame to detect bit errors. If one or more bit-errors are present in the frame it is assumed that these cannot be corrected, i.e. the frame is considered faulty and not received.

By deploying the adaptive transmit power algorithm to this model it can be explored and elaborated. Thus, this algorithm has been integrated into the model together with logging-information which at a frame to frame basis shows: the chosen transmit power level, frames that are in error, and the algorithm state information.

C. *Elaborated simulation results*

By using model-1 and the previously discussed simulation settings it is possible to estimate the total received power which is illustrated in (Fig. 5).

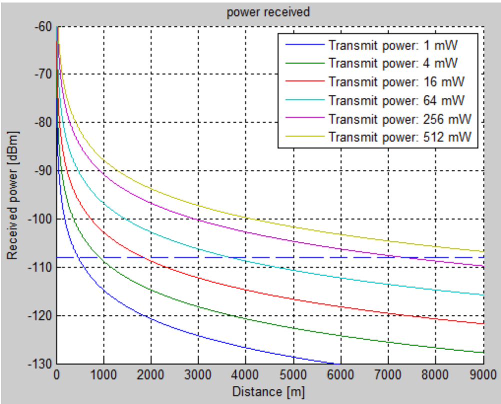

Fig. 5. The received power as a function of transmitted power and distance. The dashed line indicates the receiver sensitivity level.

As illustrated in Fig. 5 the minimum power settings (1 mW) provides a distance of approximately 0.5 km meters and the highest power settings (512 mW) a distance beyond 9 km. In this context it is noted that the datasheet for CC1125 transceiver uses a very low BER limit (10E-2) [8]. Most real world systems require a BER in the range of 10E-4 to 10E-5 [6] why the "real world" power level margin must be approximately 4 dB higher. However, as elaborated previously fluctuations in the received SNR must be expected. This means that it is not possible to select the transmit power level in a stationary manner, why it is common to add extra link-margin at the cost of extra battery power.

An alternative to a concept which uses fixed link power is an adaptive concept where the transmit power adapts to the instantaneous link and noise conditions. This has been implemented in model-2 in form of an adaptive transmit power algorithm as previously discussed.

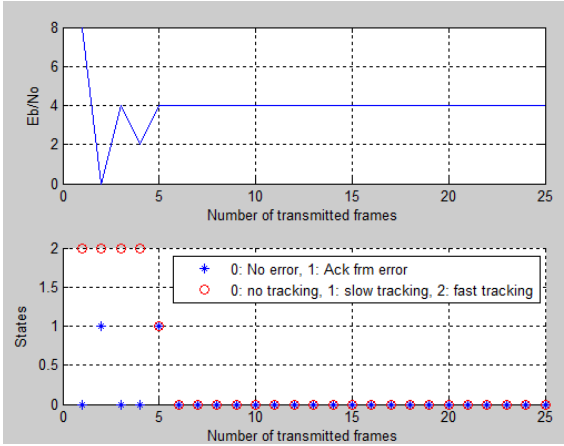

Fig. 6. Trace of the tracking algorithm. The upper figure shows SNR (Eb/N0) as a function of transmitted frame number. The lower figure shows the state-information of the tracking algorithm.

The behaviour of the adaptive transmit power algorithm is shown in Fig. 6 where the upper figure shows the used SNR (Eb/N0) as a function of the received frames. Similarly, the lower figure shows the state of the received frames (i.e. the crosses). If the state is 0 the frame is error-free, but if it is 1 the frame contains one or more errors. The circles indicate when: the algorithm does not change the power level (state 0), perform slow tracking (state 1), and perform fast tracking (state 2).

It is noted that Fig. 6 is one example run of the algorithm; nevertheless, it highlights and illustrates the important main points. The algorithm starts by setting the transmit power level to its middle value as seen in Fig. 6. Thus, the transmit power level (TPL) start with a SNR value of 10 dB. When the first error-free frame arrives the TPL adapt to this and changes its level to 0 dB. But, this level is too low why the next received frame is in error. Hence, the algorithm regulates the TPL to 3 dB where it settles, i.e. fast tracking is stopped. However, the next received frame contains errors as shown this triggers the slow tracking mechanism (circle is in state 1) which increases the TPL to 4 dB. From this point the rest of the frames are received without errors why the algorithm is in state 0, i.e. no tracking. It is noted that if one or more error-frames were received the slow-tracking algorithm would have increased the TPL further.

The energy savings which can be achieved by regulating the transmit power adaptively is shown in Fig. 7. The x-axis is transmitted bytes in the ZigBee frame and the y-axis is energy savings in percent. The lines in the figure map the energy usage as a function of number of transmitted bytes and the used transmit power level. It is noted that the energy usages are normalized with the highest energy value, i.e. a 24 dBm TPL with 128 bytes of payload. Some examples illustrate the possible savings. For example, regulating the power level down from 24 dBm to 18 dBm with a frame length of 128 bytes saves 52 percent energy per frame. Similarly, regulating down to 10 dBm and shorten the frame length to 60 bytes saves 80 percent.

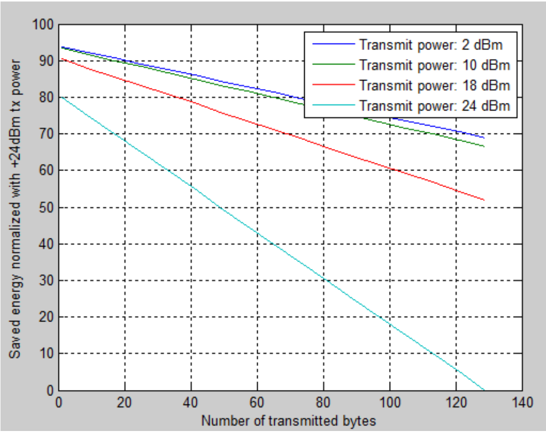

Fig. 7. Normalized saved energy as a function of transmit power and number of bytes transmitted. The highest setting (24 dBm and 128 bytes set to 100 percent and used for the normalization).

These energy savings can be visualized and elaborated in the light of using a solar power resource as discussed in [1]. The results of combining the settings from [1] with the adaptive transmit power algorithm is shown in Fig. 8.

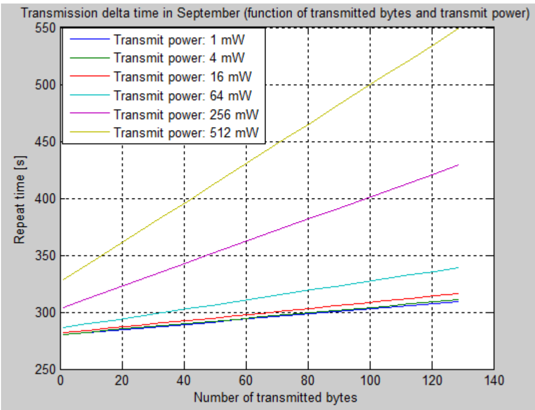

Fig. 8. The time between each transmission as a function of message length, transmit power and solar power available in september month (Denmark)

The "repeat time" shows how often a message can be send as a function of message length and the used transmit power. This provides some insight into the compromises that are needed with respect to the used average energy level provided by the solar cell. An example is using a TPL of 256 mW (24 dBm) which means that a message of length 128 bytes can be repeated every 430 second. However, lowering the TPL by using the adaptive algorithm to e.g. 64 mW (18 dBm) with the same payload length the messages can be repeated every 340 seconds. It is noted that often it is possible to shorten the transmitted messages considerably as discussed previously. Using a shorter message provides additional savings, i.e. an adaptive link can be established which reduces the energy consumption and thereby sustain the usage of solar power as the main power source.

More generally, in addition to an adaptive transmission power algorithm similar IoT device behaviours can be programmed into its embedded microcontroller and thereby enable it to behave pseudo-intelligently. Such behaviour can be remotely programmed into it in form of manually setup the needed parameters. An example could be the time before harvest (September for many grain types in Denmark) where the farmer decides to monitor the humidity in the grain and therefore program the field IoT device to only transmit these data with a fixed time interval. Similarly, an pseudo-intelligence system in the IoT device could monitor the available battery-power and regulate the transmitter parameters further. So, if the field IoT devices has been running for some time without any harvested power the transmit parameters can be adjusted so the battery last longer and when the solar energy is back on the parameters can be adjusted so the battery charges between the transmissions.

V. Conclusion

An energy efficient adaptive wireless link for farms which uses an adaptive transmission power algorithm has been explored and elaborated by using two simulation models. These models simulate the vital parameters in a wireless link based on ZigBee technologies and real world hardware in form of the transceiver module CC1125 from Texas Instruments. It has been found that it is possible to place a wireless IoT device far from the farm-controller by using the elaborated adaptive technology. Hence, power savings in the range from 50 to 70 percents can be achieved by regulating the transit power level instead of setting it to the much higher fixed level which includes a considerable safety margin. Similarly, considerable savings can be achieved by adjusting the amount of payload so it is sufficient to transmit vital data like those presented and discussed previously in the bee life monitoring scenario. Additionally, the presented simulation results support and enable a future design of adaptive algorithms for IoT nodes, i.e. algorithms could scale the IoT node power consumption according to weather conditions and thereby behave adaptive with respect to the sustainable power available.

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