Simple Prediction-Based Power Control for the On-Body Area Communications Channel

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Abstract—Methods for transmit power control based on simple long-term channel prediction for the general body-area communications channel are presented. The power control methods are based on large sets of empirical every-day activity data. Numerous transmit-receive pair (Tx-Rx) locations on the human body, i.e. on-body, for a typical body-area-network (BAN) are considered. With the use of a simple prediction method based on held samples, and an enhanced held simple prediction method that uses short term mean path loss with the held sample, optimal power allocation for long-term transmit power control is described. When tested, according to the draft IEEE 802.15.6 BAN radio standard, on empirical data, both power allocation methods are shown to be more reliable, and also more energy efficient in terms of transmit circuit power consumption, than systems that use typical set Tx power levels for BAN.

I. INTRODUCTION

Wireless communication between multiple sensor devices attached to the body inspires the need for a wireless Body Area Network (BAN) [1]. Applications for BANs [2] include health-care, sporting and military uses, with health-care likely to be the first substantial use. In consideration of the technical requirements for BAN, and the use in health-care, long-term, reliable low-power communication is vitally important, with low-complexity sensor nodes. Thus to facilitate long-term low-power operation, adaptive power control is a possible solution, which should also improve reliability.

There are various descriptions of propagation characteristics for on-body communications e.g. [3], which are all based on empirical data. However most of these descriptions are based on orchestrated scenarios (i.e. set activities), and do not capture channel dynamics. There have also been some studies of propagation statistics related to human body movement, or channel dynamics, both narrowband and ultra-wideband e.g. [4], [5], but these are also orchestrated scenarios. The basis of the work here is large sets of empirical data using wearable channel sounders, with a large variety of adult human subjects, engaged in every-day activity, generally over periods of two hours or more. The capturing of such dynamic channel data, as well as facilitating good over-all characterization of the BAN channel¹, enables the development and testing of

algorithms and schemes that can be used to enhance WBAN communications, such as power control.

In the case of the work described here, the data was analyzed with the objective to answer: -

- 1) Is it possible to use very simple long-term channel prediction in the BAN channel, with acceptable reliability?
- 2) Can this channel prediction be used, in conjunction with the empirical data, to provide adaptive power control methods, that reduce transmit circuit power consumption, and improve reliability, given likely Rx power sensitivities?
- 3) Given likely beacon periods, and intervals between the sending of packets for a given hub to sensor link, in standards-compliant BAN, is simple adaptive power control still feasible?
- 4) Is it possible to further enhance the adaptive power control, with a very small increase in complexity?

We demonstrate that effective long-term channel prediction, with suitable adaptive power control, is possible, which can reduce overall power consumption and increase performance reliability, in terms of outages, and hence packet error rates, of the BAN communications link; and we give recommendations for the power control settings. Further an enhancement of the power control method is suggested which further improves performance. For both power control methods good performance improvement is found at draft standards specified receive sensitivities, and beacon periods, for prediction intervals up to, and far in excess of delay requirements for the draft IEEE technical requirements.

A description of the experimental method follows in the next section. Section III provides description of the recommended power control methods, based on the simple channel prediction described there; and also gives some background on IEEE standards Tx/Rx power requirements. Section IV gives relevant performance analysis in terms of power savings and reliability in implementing the power control methods. Finally Section V provides some concluding remarks.

II. EXPERIMENTAL SETUP

The experimental set-up was for on-body area communications encompassing every-day activity of long periods using multiple small body-mounted radios/channel sounders as Tx and Rx. An image of the channel sounder is shown in Fig. 1. This activity is predominantly that of an office-worker over several hours in an indoor office, at home, and jogging in an

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¹First and Second order statistics for this data can be found in [6].

TABLE I
CHANNEL SOUNDERS PLACEMENTS; R,L-Right,Left. A:ANKLE,K:KNEE,E:ELBOW,H:HIP,W:WRIST

RECEIVER (Rx) LOCATIONS	TRANSMITTER (Tx) LOCATIONS									
	RIGHT HIP					LEFT CHEST				
FRONT	RA	LA	RK	LK	RW	LW	RE	LE	LH	HEAD
BACK	RA	LA	RK	LK	RW	LW	RE	LE	LH	RH

Fig. 1. Picture of the channel sounder used

Fig. 2. Full map of Tx/Rx positions for On-Body Measurements

outdoor suburban environment. The measurements were made near the 2.4 GHz ISM band (2360 MHz), one of the candidate carrier frequencies for the IEEE 802.15.6 BAN standard [7].

The channel sounders were placed on 10 adult test subjects (there were multiple measurement datasets for some subjects, made at different times) where the radios used a Chipcon CC2500 2.4 GHz low power transceiver. Full description of the channel sounders can be found in [8]. Subjects wore a varying amount of these radios, with some operating as Rx, some as Tx and Rx, and some as Tx (the total amount of Tx and Rx varied from 3 to 20). The complete map of all Tx/Rx positions is shown in Fig. 2, these are also given in Table I. Individual subject measurements generally lasted for a period of two hours or more. Channel gain measurements, were made in this case using the RSSI (Received Signal Strength Indicator) digital log made upon successful packet detection by the radios. A total of 140 Tx/Rx link measurements were made over all test subjects.

III. SIMPLE CHANNEL-PREDICTION BASED POWER CONTROL FOR BAN

A. IEEE Standards Requirements of Rx Sensitivities and output Tx power

In order to implement effective power control, it is necessary to know IEEE 802.15.6 standards-compliant Tx/Rx power specifications. According to the IEEE 802.15 Task Group 6

draft standard, [9] for operation at 2400 MHz (particularly in the 2360–2483.5 MHz band), four information Data Rates, R_D , need to be supported, with associated minimum receive power sensitivities Rx_{sens} . These are given in Table II below. All standards compliant devices must be able to output Tx power, $Tx_{out} = -10$ dBm (at least), with the maximum allowed $Tx_{out} = 0$ dBm, [9].

TABLE II
BAN COMPLIANT DATA RATES, R_D , AND ASSOCIATED MINIMUM Rx_{sens} FOR OPERATION AROUND 2.4 GHz

R_D kbps	121.4	242.9	485.7	971.4
Rx_{sens} dBm	-95	-93	-90	-86

Any BAN device will be required to operate in Tx and Rx mode. Here we describe measures of effective power control and reliability in Tx mode (which accounts for just under one-half of power consumption in BAN [10]).

B. Power Control Method

We assume the power control is applied at the sensor node, prediction can occur at gateway or sensor node due to channel reciprocity, and the less power constrained gateway device transmits at a constant power, which in these examples is 0 dBm. For the purposes of power control it is assumed that the sensor node in the BAN can vary its Tx_{out} from -30 dBm to 0 dBm in 0.5 dBm steps. We present algorithms, which are essentially similar, but different in specific power settings for each of the prescribed $Rx_{sens} = -95, -93, -90$ and -86 dBm respectively.

Due to the inherent long-term temporal stability of the everyday BAN channel, we present power control based on channel prediction up to 1s in to the future, where spacing between received packets for a given link varies from 10 ms to 400 ms (corresponding to typical particular beacon, or superframe, periods in BAN devices). Effective *channel prediction can be based on using the last sampled received signal strength*, or channel gain, which can be measured at the gateway device, or at the sensor for the Tx/Rx link of interest. It is also assumed that the nominal Rx_{sens} of the devices is also known, which can be inferred from the data rate R_D . Thus we propose predictive power control where the sensor node transmits at a specific power over the prediction interval, which may be over the duration of several superframes, for multiple packets, based on the last received signal strength. This can further be enhanced by using a short term root-mean-square power to guide power allocation, and improve reliability, with only marginal change in power consumption. Here we present the baseline power control method, Algorithm 1, and enhanced

method, Algorithm 2, which uses information about the short term mean.

Algorithm 1 Power Control at 4 receive sensitivities, baseline, for T_{pred} samples into the future

Last received RSS amplitude = $\text{mag}(\ell)$
 $Rx_{\text{sens}} = [-95, -93, -90, -86]$ dBm, $k = 1, 2, 3, 4$
 $\text{levels}_k = [Rx_{\text{sens}}(k), Rx_{\text{sens}}(k) + 2.5, \dots, Rx_{\text{sens}}(k) + 45]$ dBm
Scaling factors $\mathbf{a} = [7.5, 10, 7.5, 5]$ dB
Scaling factors $\mathbf{b} = [1, 0, 1, 1]$ dB
Find index k , based on data rate R_D
Find index i so $\text{levels}_k(i-1) < \text{mag}(\ell) \leq \text{levels}_k(i)$
 $C = Rx_{\text{sens}}(k) + a(k)$ dBm
if $\text{levels}_k(i) \leq C$ dBm **then**
 $Tx_{\text{out}}(1, 2, \dots, T_{\text{pred}}) = 0$ dBm
else if $C + 2.5 \leq \text{levels}_k(i) \leq C + 30$ dBm **then**
 $Tx_{\text{out}}(1, \dots, T_{\text{pred}}) = C + b(k) - \text{levels}_k(i)$ dBm
else
 $Tx_{\text{out}}(1, \dots, T_{\text{pred}}) = -30 + b(k)$ dBm
end if

Algorithm 2 Enhanced Method Power Control at 4 receive sensitivities for T_{pred} samples into the future

Last received RSS amplitude = $\text{mag}(\ell)$
 $Rx_{\text{sens}} = [-95, -93, -90, -86]$ dBm, $k = 1, 2, 3, 4$
 $\text{levels}_k = [Rx_{\text{sens}}(k), Rx_{\text{sens}}(k) + 2.5, \dots, Rx_{\text{sens}}(k) + 45]$ dBm
 $\mu_{\text{rms}} = \sqrt{\left(\sum_{j=\ell-4T_{\text{pred}}+1}^{\ell} \text{mag}(j)^2 \right) / (4T_{\text{pred}})}$
if $\mu_{\text{rms}} > -74$ dBm **then**
 $\mathbf{a} = [10, 10, 10, 7.5]$ dB
 $\mathbf{b} = [1, 1, 0, 0]$ dB
else if $\mu_{\text{rms}} \leq -74$ dBm **then**
 $\mathbf{a} = [7.5, 7.5, 5, 5]$ dB
 $\mathbf{b} = [0, 0, 1, 1]$ dB
end if
Find index k , based on data rate R_D
Find index i so $\text{levels}_k(i-1) < \text{mag}(\ell) \leq \text{levels}_k(i)$
 $C = Rx_{\text{sens}}(k) + a(k)$ dBm
if $\text{levels}_k(i) \leq C$ dBm **then**
 $Tx_{\text{out}}(1, 2, \dots, T_{\text{pred}}) = 0$ dBm
else if $C + 2.5 \leq \text{levels}_k(i) \leq C + 30$ dBm **then**
 $Tx_{\text{out}}(1, \dots, T_{\text{pred}}) = C + b(k) - \text{levels}_k(i)$ dBm
else
 $Tx_{\text{out}}(1, \dots, T_{\text{pred}}) = -30 + b(k)$ dBm
end if

IV. PERFORMANCE ANALYSIS

Results of extensive testing of the two power control methods over all channel sounder datasets will now be presented, in terms of average power consumption in Tx mode, percentage outage, and error fraction with respect to transmitting with

a fixed power. Of course to estimate circuit power savings in Tx mode we need to map Tx_{out} to transmit power consumption, Tx_{cons} . The MedWin alliance in IEEE 802.15.6, [10], has stated $Tx_{\text{cons}} = 2.9$ mW for $Tx_{\text{out}} = -10$ dBm at 2.4 GHz; and to determine relative power consumption with respect to this $Tx_{\text{out}} = -10$ dBm reference power, we use the power consumption curve for -30 dBm to 0 dBm with respect to BAN devices provided in [11]. Thus Tx_{cons} ranges from 1.76 mW at $Tx_{\text{out}} = -30$ dBm to $Tx_{\text{cons}} = 5.97$ mW at $Tx_{\text{out}} = 0$ dBm.

In Fig. 3 average circuit power consumption is shown for power control 400 ms ahead, Fig. 3(a), and 1000 ms ahead, Fig. 3(b) and with period between link samples, which is the assumed superframe period, ranging from 10 ms to 400 ms, both baseline algorithm (1), called “Hold” method, and enhanced algorithm (2), “Enhanced Hold” method, are shown. It is clear from Fig. 3(a) that for each method power consumption

(a) Tx power consumption, power control 400 ms ahead

(b) Tx power consumption, power control 1000 ms ahead

Fig. 3. Transmit (Tx) Mode Power consumption with predictive power control

is relatively constant and independent of the period between link samples. It can be seen in Fig. 3(a) that with a receive sensitivity of -95 dBm and -93 dBm, the hold and enhanced methods both consume less power, between 3% and 15% less than transmitting with a constant power of -10 dBm. At a receive sensitivity of -90 dBm, the circuit power consumption is marginally greater than that at constant $Tx_{out} = -10$ dBm, and at -86 dBm there are power savings over constant Tx_{out} at -7.5 dBm. For all schemes there are significant power savings over constant transmission above -7.5 dBm.

Percentage outage, for both power control methods, at the four receive sensitivities, for predictive power control 400 ms ahead is shown in Fig. 4. It is noted that apart from the “Hold” method at $Rx_{sens} = -86$ dBm, all methods have outage significantly less than 10% outage, between 3% and 5.5% for all Rx_{sens} less than -86 dBm, and around 9% for the “Enhanced Hold” method at $Rx_{sens} = -86$ dBm. It is noted that this outage provides a lower bound on average packet-error-rate, which for BAN, according to the draft standard [9], should be less than 10%. It can thus be concluded that in most cases, for the predictive power control presented, this requirement for reliable operation of the draft BAN standard can be met with both predictive power control methods, but particularly with the “Enhanced Hold” method.

In Fig. 5 we present results for outage percentage and average power consumption for the particular case of Tx/Rx link sample spacing, i.e. superframe duration, of 50 ms, for Enhanced Hold power control 250 ms ahead, 400 ms ahead and 800 ms ahead. For comparison the results for “Do Nothing”, transmitting at constant power of -10 dBm or greater, are shown. As expected both outage percentage, Fig. 5(a), increases, from around 4% to around 9%, which meets requirements for reliable operation in terms of outages, and average power consumption increases in Fig. 5(b), from around 2.65 mW to around 3.25 mW. Outage percentage for trans-

mitting at constant power is worse when $Tx_{out} = -5$ dBm or less, and in all but the lowest Rx_{sens} , $Tx_{out} = -10$ dBm always exceeds the 10% maximum outage allowed. Power consumption savings are generally improved over all “Do Nothing” cases, and always improved over constant $Tx_{out} \geq -7.5$ dBm. Importantly, as the prediction interval increases from 250 ms to 800 ms outage percentage increases by up to 2.5% in Fig. 5(a), and power consumption increases by up to 0.1 mW in Fig. 5(b). The only slight divergence from this trend is a 0.05mW increase in power consumption at -86 dBm receive sensitivity predicting 400 ms ahead when compared with predicting 800 ms ahead.

The final key performance measure, is to demonstrate the ratio of errors, where an error (or outage) is incurred when transmitting at a power less than that required to sustain reli-

Fig. 4. Percentage Outage, Predictive Power Control 400 ms ahead

(a) Outage Percentage

(b) Average Tx power consumption

Fig. 5. Transmit (Tx) Mode Outage and Power consumption, 50 ms link sample spacing, Enhanced Hold power control 250 ms to 400 ms ahead, in terms of Rx_{sens}

able communication; between the enhanced method, and doing “nothing” transmitting at constant power. An error ratio < 1 indicates an improvement in performance using the enhanced method. Results of this analysis is shown in Fig. 6. In Fig. 6(a), with 50 ms link sample spacing, for the enhanced method there is predominantly less than 1/2 errors (mostly around 1/3) of that of transmitting constantly at -10 dBm. In Fig. 6(a) for constant $T_{xout} = -5$ dBm, Tx mode power consumption is 3.9 mW, much greater than the predictive power control proposed here. Apart from predicting 250 ms and 400 ms ahead with $R_{xsens} = -95$ dBm, the predictive power control is more reliable than the “Do Nothing” alternative of transmitting at a constant power of -5 dBm, despite the “Do Nothing” option consuming much more power than predictive power control. In terms of errors in Fig. 6(a), significant improvement occurs for $T_{xout} = 0$ dBm constant output power, but when compared with simple predictive power control, the approximate doubling of power consumption means this is far less feasible for a BAN sensor node. Fig. 6(b) provides a different perspective on this error ratio, showing results for predicting approximately 400 ms ahead, with 10 to 400 ms spacing between link samples. Two “Do Nothing” cases are presented in Fig. 6(b), $T_{xout} = -10$ dBm and $T_{xout} = -5$ dBm, for the four receive sensitivities, in all but the instance of $T_{xout} = -5$ dBm at $R_{xsens} = -95$ dBm there are significantly fewer errors (or outages) when using the “Enhanced Hold” method when compared with transmitting at a constant power.

V. CONCLUDING REMARKS

Simple and effective predictive power control for on-body area communications has been presented, enabled and verified by extensive empirical testing. This has the potential to significantly improve sensor battery lifetime, and on-going low power BAN sensor node operation, in conjunction with improved reliability. Such predictive power control is also compliant with the IEEE 802.15.6 proposed BAN standard. The simplicity of the power control is such that the baseline method could be implemented in the sensor node, but for the enhanced method, with a simple few-bits feedback channel from the hub to the sensor, the hub could conceivably direct the power output of the sensor without requiring any decision to be made at the sensor node. Simple predictive power control, as demonstrated here, should be an integral part of future BAN development.

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(a) Error Ratio, 50 ms link sample spacing, in terms of Rx. sensitivity

(b) Error Ratio, Power Control 400 ms ahead, in terms of time period between link samples

Fig. 6. Error Ratio of applying “Enhanced Hold” method versus “Do Nothing”, where doing nothing applies transmitting at a constant power of -10 dBm or greater

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