Transmit Power Control for Wireless Body Area Networks using Novel Channel Prediction

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***Abstract*—We present a predictor for real Body-Area-Network (BAN) channels that is accurate for up to 2 seconds, even with a nominal channel coherence time of 500 ms. The predictor utilizes the partial-periodicity of measured BAN channels using the previous 4 seconds of channel gain values. We demonstrate use of this predictor for power control with open-access and private channel measurements. When used under a realistic setting for IEEE 802.15.6, with packet loss less than 10%, we show that the accurate channel predictor does not translate into substantial reduction in packet loss or power usage over a simple sample-and-hold method, even though it is a more accurate predictor than sample-and-hold.**

I. INTRODUCTION

The first major application of wireless networks of sensors around the body, body-area-networks (BANs) [1], is likely to be healthcare. In consideration of the technical requirements for BAN [2] and the use in health-care: long-term, reliable, low-power communication is vitally important. Adaptive power control is a possible solution that can facilitate long-term low-power operation, and also improve reliability.

The basis of the work here is large sets of empirical BAN data collected using small wearable radios, with ten adult human subjects engaged in every-day activity, generally over periods of two hours or more. Such comprehensive dynamic data for the BAN channel facilitates good overall characterization[1]. This data also enables the testing and development of schemes that can be used to enhance BAN communications, such as the power control scheme in [4], where a very simple method of effective power control using the prediction from the last held sample was presented[2].

Here the data was further analysed to answer the following:

1) Is it possible to improve long-term channel prediction over that of the held sample in the BAN channel?
2) Can this predictor be used to provide an adaptive power control method that reduces transmit circuit power consumption and improves reliability?
3) With likely periods for beacons, superframes, and intervals between packets for a given hub to sensor link, does this adaptive power control still work?
4) Is an enhancement of the power control method using a short-term mean threshold effective?

We demonstrate that effective long-term BAN channel prediction, up to 2 s ahead, is possible, and that it improves on the method of simply using the last sample held as a prediction. Partial periodicity of the fading channel is used by applying a non-traditional least squares method to weight a held sample by a previously received contiguous portion of channel gain samples. With direct power allocation based on the prediction, there are significant improvements in terms of normalized mean-square power error and bias for all BAN receive sensitivities likely at 2.4 GHz. Adaptive power control using the predictor can both reduce transmit power consumption and improve reliability. Similar to the method for a held sample in [4], adapting power allocation based on a short-term mean path loss shows good performance, and works given typical BAN superframe periods and intervals between packets for a given hub-to-sensor link.

A description of the experimental method follows in the next section. Section III provides description and analysis of the predictor, provides an algorithm adapting the predictor to effective BAN power control, 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 of the adapted power control with the predictor. Finally Section V provides some concluding remarks.

II. EXPERIMENTAL SETUP

The experimental set-up was for on-body area communications encompassing everyday activity of long periods using multiple small body-mounted radios (channel sounders) as Tx and Rx. The activity is predominantly that of an office-worker over several hours in an indoor office, at home, and jogging in an outdoor suburban environment. The measurements were made at 2360 MHz, one of the proposed carrier frequencies for the IEEE 802.15.6 BAN standard [6].

The small wearable radios were placed on 10 adult test subjects, with multiple measurements made for some subjects, at different times. One of the measurement datasets that were used is open-access [7]. A full description of the radios can be found in [8]. Subjects wore a varying number of these radios, with some operating as Rx, some as Tx and Rx, and

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[1] First and Second order statistics for this data can be found in [3].

[2] A more complex power control method, evaluated using in-body to on-body simulated data, is presented in [5].

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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

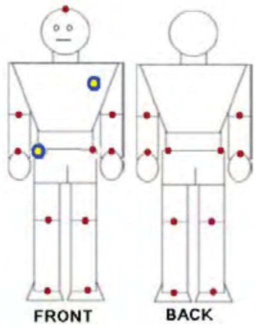

Fig. 1. Full map of Tx/Rx positions for On-Body Measurements

some as Tx (the total amount of Tx and Rx varied from 3 to 20). The complete map of all possible Tx/Rx positions is shown in Fig. 1, these are also given in Table I. Individual subject measurements generally lasted for a period of two or more hours. The digital RSSI (Received Signal Strength Indicator) log made upon successful packet detection by the radios was used to measure channel gain. A total of 140 Tx/Rx link measurements were made over all test subjects.

III. CHANNEL-PREDICTOR AND POWER CONTROL

A. IEEE Standards Requirements

According to the IEEE 802.15.6 draft standard [6], four information Data Rates (R_D) need to be supported for operation in the 2360–2483.5 MHz band; each with associated minimum receive power sensitivities (Rx_{sens}). These are given in Table II. All standards compliant devices must be able to output Tx power (Tx_{out}) of at least -10 dBm, and up to a maximum of 0 dBm, [6]. Knowledge and use of these parameters is vital to testing and operation of effective power control.

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

BAN devices are required to operate in both Tx and Rx mode. Here we describe measures of effective prediction, power control, and reliability in Tx mode (which accounts for just under half of the power consumption in BAN devices [9]).

B. Alternative Weighted Least-Squares Predictor

The method can first be illustrated in the following diagram Fig. 2. This diagram shows an example portion of a measurement for channel gain RSSI samples ($\boldsymbol{mag}$) received in a BAN link every 5 ms ($t_s = 5\ ms$); which corresponds to the RSSI sampling frequency of the channel sounder. Note that this is somewhat shorter than the relevant BAN superframe periods, but with proper adjustment for much larger sample spacing the method still applies. This portion is *partially periodic*. In this example, an interval of $N_s = 1000$ samples (i.e. last 5 s) is used. Here we attempt to predict $T_{pr} = 30$ (150 ms) samples ahead of the last received sample by using the 970 channel gain samples that precede it.

The method is to take the last n_r received samples and search over the previous $(N_s - T_{pr})$ samples to find the closest match. (In Fig. 2, $n_r = 10$; but with a lower sampling rate N_s and n_r are reduced.) The next T_{pr} samples ($\boldsymbol{S_p}$) are then predicted by using an alternate least-squares (LS) formulation that is weighted by the last received sample. The predictor can be expressed as follows:

$$
\begin{aligned}
\boldsymbol{y_s} &= \boldsymbol{mag}(L - N_s + 1, L - N_s + 2, \ldots, L),\\
\boldsymbol{x(i)} &= |\boldsymbol{y_s}\,(n_r - i + 1, \ldots, N_s - T_{pr} - i + 1) -\\
&\qquad y_s(N_s - i + 1)|^2\,, i = 1, \ldots, n_r, \qquad (1)
\end{aligned}
$$

$$\mathbf{X_s} = \sum_{i=1}^{n_r} \boldsymbol{x(i)}, \qquad (2)$$

$$i_n = \max \arg \min(\mathbf{X_s}) + n_r, \qquad (3)$$

$$
\begin{aligned}
\boldsymbol{S_p} &= (m_1.\boldsymbol{y_s}(i_n, \ldots, i_n + T_{pr} - 1) + \qquad (4)\\
&\qquad m_2.mag(L))\,/(m_1 + m_2),
\end{aligned}
$$

where $|\cdot|$ are the absolute values of the vector difference, $m_1 = 1$, and $m_2 = 2.5$ is the preferred instantiation for BAN

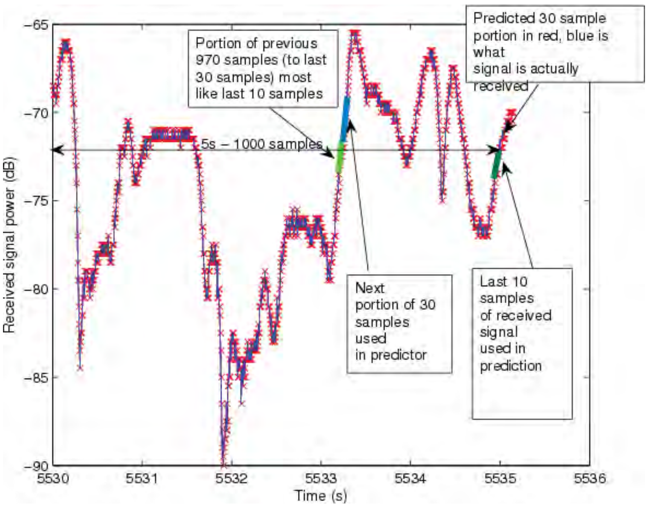

Fig. 2. Illustration measurement with application of channel predictor

according to a mean-square prediction error criterion. The best instantiation of N_s according to the same mean-square prediction error criterion is the number of samples, which changes depending on BAN superframe periods, corresponding to the last 4 s of signal (i.e., 1 s less than illustration in Fig. 2). The best values of n_r are $n_r = 5$ for t_s=10 ms, $n_r = 4$ for $t_s = 20$ ms, $n_r = 3$ for $20 < t_s < 120$ ms and $n_r = 2$ for $t_s > 120$ ms. $\boldsymbol{S_p}$ is the final predicted channel gain portion, $mag(L)$ represents the last received channel gain.

If we simply map each predicted channel gain, $S_p(\ell)$, to a power estimate, $\hat{p}(\ell)$, (which may not be practical for actual power control as no error margin is allowed), we can directly compare the performance of the predictor described by (1)-(4) to a sample-and-hold method that uses the last received sample, $mag(L)$, as an estimate of the next T_{pr} samples. A good measure of this is normalized mean square power error (NMSE) and normalized power bias, following from [10], which are given there as $E[(\hat{p}(\ell)/p(\ell) - 1)^2]$ and $E[(\hat{p}(\ell)/p(\ell)-1)]$ respectively, where $E[\cdot]$ represents the mean or expectation.

Thus in Fig. 3 we provide the relative NMSE power error of the predictor (1)-(4), and the relative NMSE power error using a held sample as prediction; for prediction intervals up to 2 s, ahead with a receiver sensitivity, Rx_{sens}, of -90 dBm, and link sampling periods varying from 10 ms to 120 ms. The error is based on the NMSE power error of these predictors relative to the NMSE power error of simply transmitting at a power of -10 dBm, which is a typical transmit power for BAN [6]. There is no trend in the relative NMSE predictor power error or the "Hold" sample predictor, hence we do not seek to fit a trend-line, but we note that for all prediction intervals from 120 ms ahead to 2 s ahead, there are large improvements shown in Fig. 3, varying from 2-fold to 100-fold improvement of the weighted alternate-least-squares predictor over the "Hold" Predictor at this sensitivity. Fig. 3 also clearly shows good prediction accuracy up to 2 s ahead, far in excess of the coherence time of 500 ms for a typical everyday BAN channel. We note the general spread of NMSE power error performance is least for predicting 1000 ms ahead. In general, many orders of magnitude performance improvement are shown for both the "Hold" method and using the predictor compared to simply transmitting at a power of -10 dBm, which might be expected given the overall median path loss of 71 dB for all measurements, and large fluctuations in signal strength for each measurement.

For further illustration, we plot the direct ratio of NMSE power error for the predictor to the NMSE power error for the "Hold" Sample predictor, as well as the direct ratio of the normalize power bias of the predictor to that of the "Hold" predictor in Fig. 4 (for a prediction interval 1s ahead, for all receiver sensitivities, Rx_{sens}, and link sample spacings, t_s, varying from 10 ms to 400 ms). Again there is no trend, so we do not attempt to fit a trend-line. As might be expected, bias ratios are larger than NMSE ratios; these bias ratios range from 0.2 to 0.65, and the NMSE power error ratios vary much more widely from 0.001 to 0.5. Thus, the proposed prediction method shows significant improvement for the predictor of (1)-(4) over using a "held" sample for the wide range of realistic BAN scenarios analysed in Fig. 3 and Fig. 4.

C. Power Control

We then adapt the power control scheme used from the sample-and-hold method described in [4] to the predicted signal portion $\boldsymbol{S_p}$ derived from (1)-(4). This power control scheme is described in Algorithm 1. The essential scaling of power allocation from estimate $\boldsymbol{S_p}$ is designed to meet targeted BAN reliability and power consumption improvements simultaneously. Here here we choose 0.5 dB steps for power allocation, in contrast to the 2.5 dB steps in [4] (this gives power savings), and different power allocation based on the short term mean path loss is adapted to slightly change the scaling of power allocation (with more power above the mean, relatively lower power below the mean as for the "Enhanced Hold" Method in

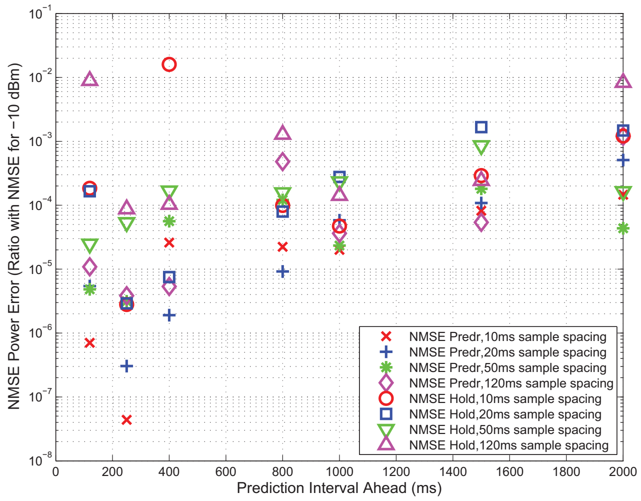

Fig. 3. Normalized Mean Square Power Error of Estimator v. Hold Method, $Rx_{sens} = -90$ dBm

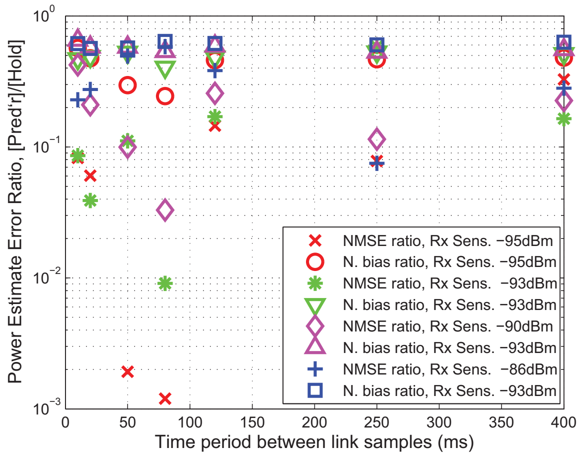

Fig. 4. NMSE power error ratio and Normalized Power Bias Ratio, of proposed predictor to hold predictor, predicting 1 s ahead

Algorithm 1 Modified Predictive Power Control at 4 receive sensitivities for $T_{\rm pr}$ samples into the future

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Find $\boldsymbol{S_p}$ (length $T_{\rm pr}$) according to (1)-(4)
$\boldsymbol{Rx_{sens}} = [-95, -93, -90, -86]$ dBm, $k = 1, 2, 3, 4$
$\boldsymbol{levels_k} = [Rx_{sens}(k), Rx_{sens}(k) + 0.5, \ldots, Rx_{sens}(k) + 40]$ dBm
$\mu_{rms} = \sqrt{\left(\sum_{j=\ell-4T_{\rm pr}+1}^{\ell} mag(j)^2\right) / (4T_{\rm pred})}$
if $\mu_{rms} > -75$ dBm then
  $\boldsymbol{c} = [9, 8.5, 7.5, 7]$ dB
else if $\mu_{rms} \leq -75$ dBm then
  $\boldsymbol{c} = [6.5, 6.5, 5.5, 4.5]$ dB
end if
for $\ell = 1, \ldots, T_{pr}$ do
  Find index $i$ so $levels_k(i-1) < S_p(\ell) \leq levels_k(i)$
  $C = Rx_{sens}(k) + c(k)$ dBm
  if $levels_k(i) \leq C$ dBm then
    $\boldsymbol{Tx_{out}}(\ell)$=0 dBm
  else if $C + 0.5 \leq levels_k(i) \leq C + 30$ dBm then
    $\boldsymbol{Tx_{out}}(\ell) = C - levels_k(i)$ dBm
  else
    $\boldsymbol{Tx_{out}}(\ell) = -30$ dBm
  end if
end for
```

[4]).

IV. PERFORMANCE ANALYSIS

Results of extensive testing of comparison of the modified predictor with the "Hold" method and "Enhanced Hold" method of [4] over all channel sounder datasets will now be presented in terms of average power consumption in Tx mode, and percentage outage. Without any explicit 2.4 GHz power consumption data to draw upon, we have used [9] and [11] as a guide to map Tx_{out} to transmit power consumption, Tx_{cons}. This was achieved by shifting the 900 MHz power consumption curve in [11] by 2.2 dB such that it passed through the $\{-10$ dBm, 2.9 mW$\}$ reference $\{Tx_{out}, Tx_{cons}\}$ point given in [9] for 2.4 GHz operation. This is of course an approximation, but it will suffice for the purposes of this paper.

In Fig. 5 average circuit power consumption is shown for power control 1 s ahead, and with sample spacing t_s varying from 10 ms to 400 ms, which are the assumed superframe periods. Both the "Hold" method [4] and the modified predictor applied in Algorithm 1 are used. It is clear from Fig. 5 that the power consumption of each method is relatively constant and independent of the period between link samples. It can be seen in Fig. 5 that with receive sensitivities of $-95, -93$ and -90 dBm, the enhanced hold methods and modified prediction methods both consume less power, between 8% and 22% less than transmitting with a constant power of -10 dBm. At a Rx_{sens} of -86 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 power transmission above -7.5 dBm.

Fig. 6 shows the outage percentage for both power control methods, using predictive power control 400 ms ahead, and compares them to the "Hold". It is noted that all methods have significantly less than 10% outage, between 3% and 5.5% for all Rx_{sens} less than -86 dBm, and around 8% for the "Modified Predictor" method at $Rx_{sens} = -86$ dBm. In general, the "Modified Predictor" method provides a 0.5% to 1% improvement over using the "Hold" method. It is noted that these outages provide a lower bound on average packet error rate, which for BAN should be less than 10% [6]. It can thus be concluded that in most cases for the predictive power control presented, reliable operation according to the draft IEEE BAN standard can be achieved.

In Fig. 7 we present results for outage percentage and average power consumption for the particular case of Tx/Rx link sample spacing, $t_s = 50$ ms, for predictive power control

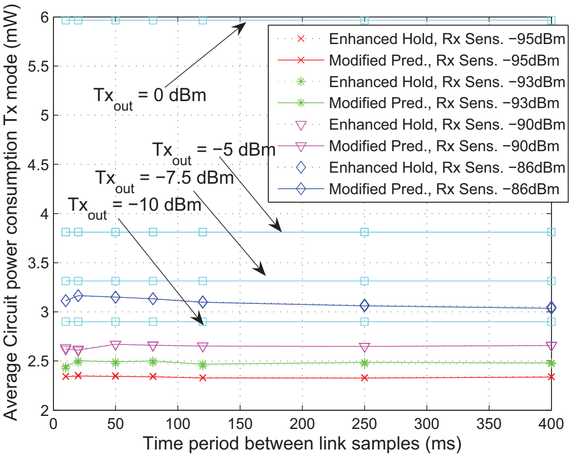

Fig. 5. Transmit (Tx) Mode Power consumption with Modified predictive power control 1000 ms ahead

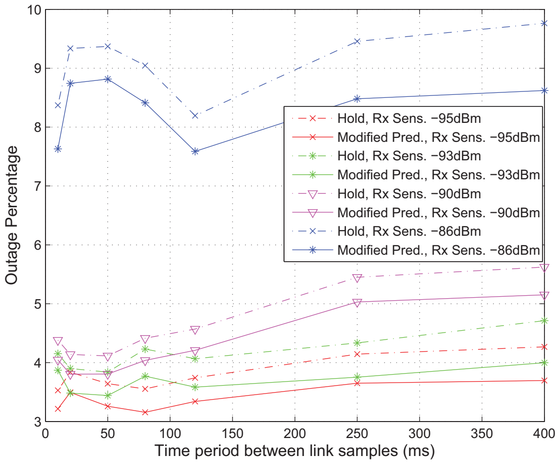

Fig. 6. Percentage Outage, Predictive Power Control 400 ms ahead

250 ms, 400 ms, 1000 ms, and 2000 ms ahead. We also provide these results for the "Enhanced Hold" method [4], and results for "Do Nothing", transmitting at constant power of -10 dBm, or greater, as comparison. Outage percentage, Fig. 7(a), increases from around 3% to around 9%, which meets the condition for reliable operation in terms of outages. Average power consumption increases in Fig. 7(b) from around 2.4 mW to around 3.2 mW. Outage percentage for predictive power control is approximate to transmitting at a constant $Tx_{out} = -5$ dBm or less. In all but the lowest Rx_{sens}, outage percentage for $Tx_{out} = -10$ dBm is significantly greater than predictive power control. The outage percentage for constant $Tx_{out} = -10$ dBm exceeds 10% for Rx_{sens} above -93 dBm. Power consumption savings are generally made over all "Do Nothing" cases, with savings always over constant $Tx_{out} \geq -7.5$ dBm. As the prediction interval increases from 250 ms to 2 s outage percentage increases by up to 3% in Fig. 7(a) for each Rx_{sens}. Power consumption varies by up to 0.35 mW in Fig. 7(b), with the least sensitive receiver. Importantly, there is only very minor improvement in terms of the reliability of predictive power control over the "Enhanced Hold" method shown in Fig. 7(a), where there is almost identical power consumption over the range of receive sensitivities.

V. CONCLUDING REMARKS

A novel long-term channel predictor particularly suited to the on-body area communications channel has been presented. It utilizes the partial periodicity of the BAN channel and weights an alternate least-squares estimate for the desired prediction interval using the last 4 s of received signal. As a predictor it performs significantly better than using a single held sample for prediction. When mapped to a suitable power allocation scheme for proper BAN operation, there are concurrent improvements in reliability and power consumption in comparison to some typical BAN transmission strategies with no channel prediction. When applied to sensible power control, it generally performs a little better than using a held sample alone, but only gives very minor improvement over the enhanced method where the "held" sample is based on a short-term mean path loss of the BAN channel.

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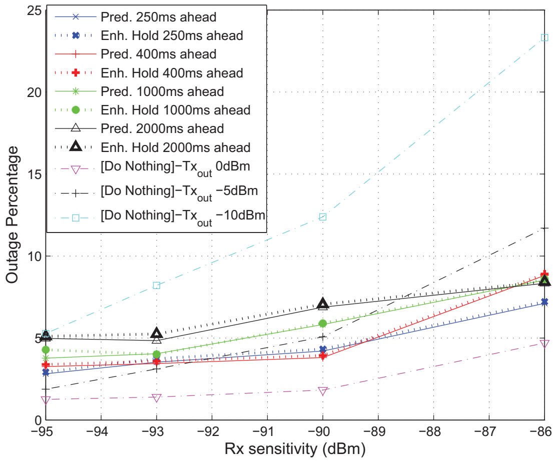
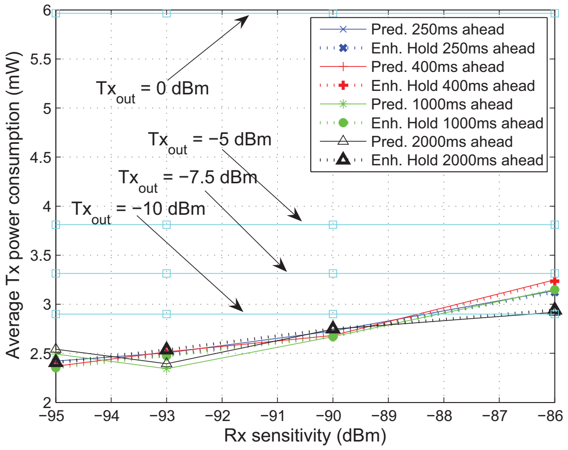


(a) Outage Percentage



(b) Average Tx power consumption

Fig. 7. Transmit (Tx) Mode Outage and Power consumption, 50 ms link sample spacing, Power control using Modified Predictor, 250 ms to 2 s ahead, in terms of Rx_{sens}

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