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ROBUST RSSI REGULATION IN WBANs VIA REDUCED-ORDER APAPTIVE POLE PLACEMENT:A COMPARATIVE STUDY

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ABSTRACT

Optimizing transmission power in Wireless Body Area networks (WBANs) is critical for balancing energy efficiency with link reliability. This paper addresses the challenge of regulating the Received Signal Strength Indicator (RSSI) under highly dynamic channel conditions caused by body posture changes. We propose a robust Indirect Adaptive control framework, comparing two methodologies: Model Reference Adaptive Control (IMRAC) and Adaptive Pole Placement Control (APPC). To overcome the ill conditioning

Caused by non -coprime polynomials in the full-order plant model, we introduce a novel implementation using a controllable reduced- order model. The control laws utilize Recursive Least Squares (RLS) with a forgetting factor for real-Time parameter tracking. Simulation results demonstrate that the APPC strategy yields superior performance, achieving a Mean Squared Error (MSE) of 0.09dBm compared to 0.52dBm for IMRAC. The proposed reduced-order APPC offers a computationally efficient and robust solution for stabilizing WBAN links against severe motion artifacts.

I. INTRODUCTION

Wireless Body Area Networks (WBANs) represent a cornerstone technology for ubiquitous healthcare, enabling continuous monitoring of physiological parameters through wearable and implanted sensors. However, the stringent energy constrains of battery-operated nodes impose significant challenges on network longevity [1]. The primary consumer of energy in sensor nodes is the Radio Frequency (RF) transceiver. Consequently, optimizing Transmission Power Control (TPC) is paramount.

The on-body RF channel is characterized by extreme volatility. Factors such as rapid body posture changes, tissue absorption, and multipath fading cause the Received Signal Strength Indicator (RSSI) to fluctuate unpredictably [2].Traditional static power assignment strategies are inefficient, leading to either excessive energy waste(over-provisioning) or frequent packet drops (under-provisioning).

Existing solutions range from simple feedback loops to complex predictive algorithms. While recent studies have explored Machine Learning (ML) and Deep Learning (DL) for channel estimation [3],[4], these methods often require computational resources that exceed the capabilities of ultra – low – power sensor nodes.

Conversely, classical control approaches like PID often fail to adapt to the time- varying nature of the WBAN channel.

This paper proposes an Indirect Adaptive Control approach that balances computational simplicity with robust performance. Building on the stochastic modeling foundation established in [5], we address a critical gap in previous implementations: the mathematical singularity arising from non- distinct poles and zeros in the plant model.

Our main contributions are:

1. Robust Formulation: Introducing a Reduced – Order Model approach to resolve the non-coprimality issue, enabling the robust application of adaptive Pole Placement.
2. Performance Benchmarking: A rigorous quantitative comparison between IMRAC and APPC in regulating RSSI under severe disturbance scenarios.

II. SYSTEM MODELING AND IDENTIFICATION

The dynamics of the RSSI, driven by transmission power and body movements, are modeled as a discrete-time Single- Input Single –Output (SISO) system.

A. The Augmented Plant Model

The variation in RSSI (y) relative to transmission power (u) and the stochastic posture noise (w) is described by linear difference equation derived from the state- space model [5]:

$$A(z^{-1})y(k) = B(z^{-1})u(k) + w(k)$$

The nominal transfer function $G_p(z)$ is given by:

$$G_p(z) = \frac{b_3z^3+b_2z^2+b_1z+b_0}{z^4+a_3z^3+a_2z^2} \qquad (1)$$

B. Model Order Reduction

Analysis of the full-order model (Eq.1) using experimental data reveals that the polynomials $A(z^{-1})$ and $B(z^{-1})$ are nearly non-coprime (i.e, they share common factors).This ill- conditioning causes the Sylvester matrix to become singular, rendering standard pole placement algorithms unstable. To ensure controllability and observability, we approximate the system using a Reduced-Order Model$G_r(z)$:

$$G_r(z) = \frac{b_1'z+b_0'}{z^2+a_1'z+a_0'} \qquad (2)$$

This approximation captures the dominant dynamics of the link while ensuring a robust solution to the Diophantine equation required for control synthesis.

c. Online Parameter Estimation (RLS)

T track the time- varying parameters $\theta = [a_1', a_0', b_1', b_0']^T$, we employ the Recursive Least Squares (RLS) algorithm with an exponential forgetting factor $\lambda(0.95 \le \lambda \le 0.99)$. The estimator minimizes the error cost function:

$$J(\theta) = \sum_{i=1}^{k} \lambda^{k-i} \left(y(i) - \Phi^T(i-1)\hat{\theta}(k)\right)^2$$

Where $\boldsymbol{\Phi}$ is the regression vector. This ensures the control law adapts instantaneously to new body postures.

III. ADAPTIVE CONTROL STRATEGIES

We investigate two distinct adaptive strategies applied to the reduced0order WBAN model.

A. Indirect Model Reference Adaptive Control(IMRAC)

IMRAC aims to force the plant output y_p to track a reference model $W_m(z)$ output y_m

$$y_m(k) = W_m(z)r(k) = \frac{1}{z}r(k)$$

The control law is algebraically synthesized to cancel the plant's poles and zeros and replace them with those of W_m. While effective for minimum- phase systems, IMRAC can exhibit large transient oscillations if the plant model zeros are poorly damped.

B. Adaptive Pole Placement Control(APPC)

APPC is designed to place the closed-loop poles at specific locations determined by a polynomial $A^*(z)$ to achieve desired stability and settling time properties. The control input is:

$$u(k) = \frac{T(z)}{R(z)}r(k) - \frac{S(z)}{R(z)}y(k)$$

The polynomials $R(z)$ and $S(z)$ are obtained by solving the Diophantine Equation:

$$\hat{A}(z)R(z) + \hat{B}(z)S(z) = A^*(z)A_0(z)$$

By utilizing the reduced- order model, we guarantee that $\hat{A}$ and $\hat{B}$ are coprime, ensuring a unique and stable solution. The desired poles were chosen to provide a critically damped response, minimizing overshoot, which is crucial for maintaining stable link quality.

IV. SIMULATION AND RESULTS

The proposed control schemes were validated using MATLAB/Simulink. The target RSSI was set to -85 dBm. The simulation introduced abrupt step changes in the system parameters to emulate sudden athletic movements (e.g, running to stopping).

A. Comparative Analysis

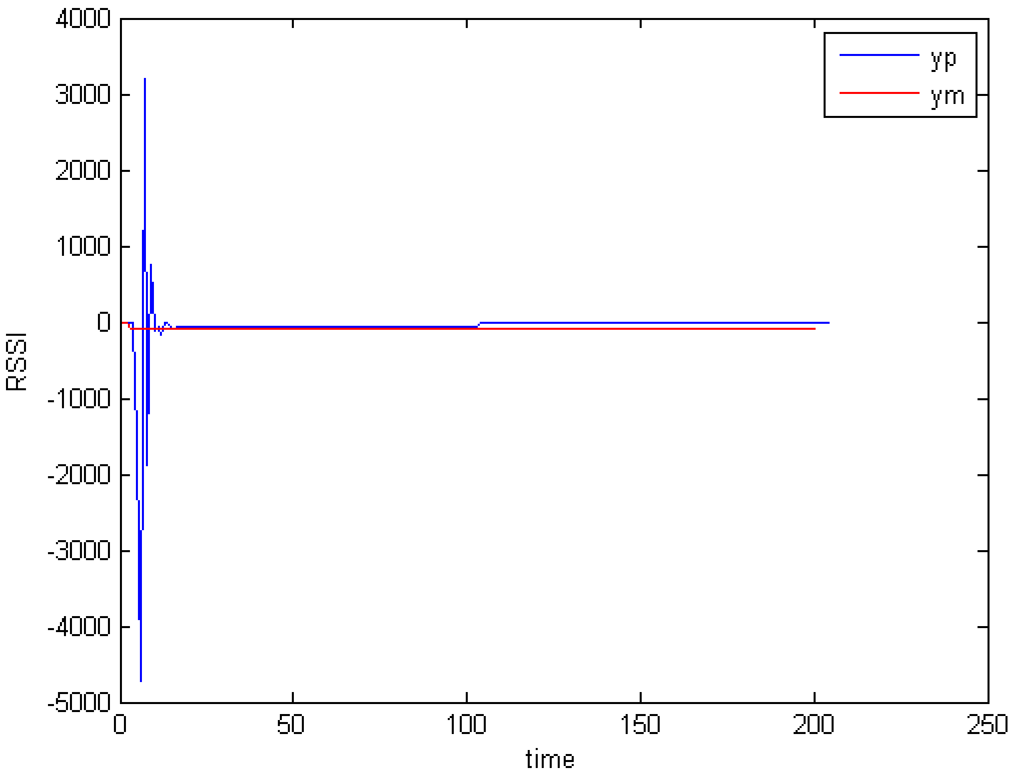

Figure (1) the RSSI response for IMRAC Simulation

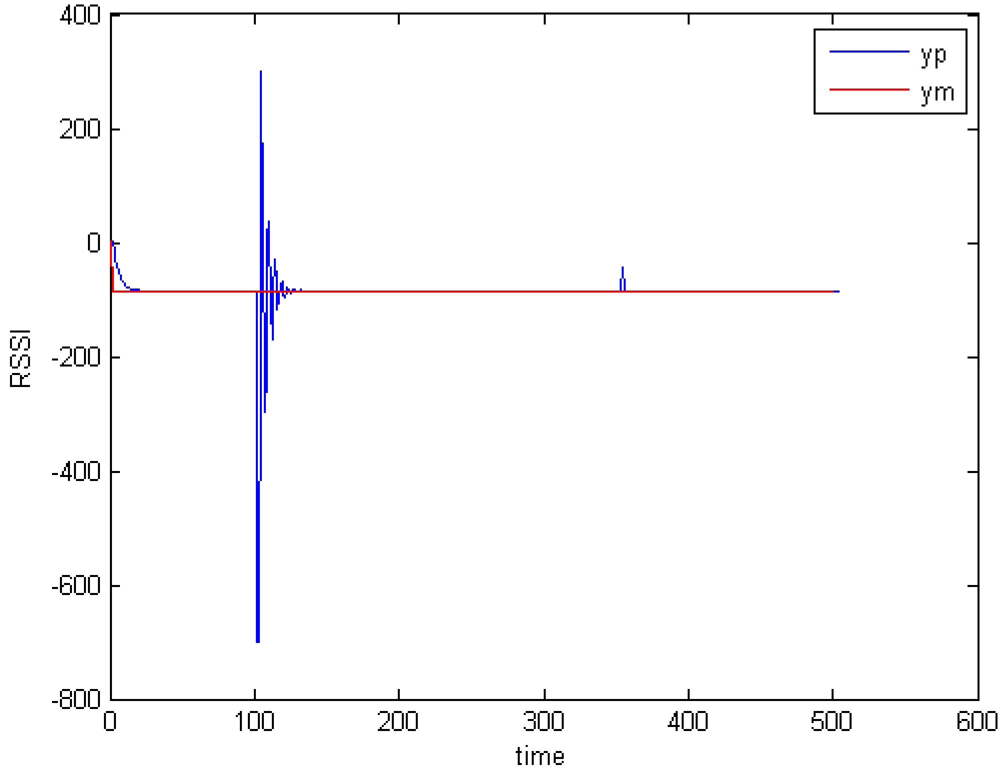

Figure (2) the RSSI response for APPC Simulation

1. IMRAC The IMRAC controller successfully stabilizes the system but exhibits a noticeable steady-state error and slower convergence when parameters change abruptly. This is attributed to the limitations of exact model matching in the presence of stochastic noise.
2. 2. APPC Response: the APPC controller demonstrates superior performance. It tracks the reference signal -85 dBm with high precision and rejects disturbances rapidly. The reduced-order formulation effectively filters out high- frequency noise.

B. QUANTITATIVE PERFORMANCE METRICS

Table I presents the Mean Squared Error (MSE) for both controllers.

TABLE I: PERFORMANCE COMPARISON

Control Strategy	MSE	Settling Time	Robustness
IMRAC	0.52	Moderate	Medium
APPC	0.09	Fast	High

The APPC method reduces the tracking error variance by approximately 82% compared to IMRAC. This reduction directly translates to energy savings, as the transceiver avoids unnecessary power fluctuations.

Conclusion

This paper presented a robust adaptive power control mechanism for WBANs. By diagnosing the non- coprimality issue in existing models and implementing a Reduced-Order Adaptive Pole Placement strategy, we achieved stable and precise RSSI regulation. The APPC method outperformed IMRAC significantly in terms of tracking accuracy (MSE=0.09). These results suggest that complex learning-based methods for resource-constrained body sensor networks.

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