

Link Layer Adaptation in Body Area Networks: Balancing Reliability and Longevity

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Abstract—A wireless Body Area Network (BAN) consists of multiple radio-enabled wearable and implantable sensor nodes for use inside or in proximity to the human body. BANs are expected to balance requirement for reliable communication of their nodes with a need for battery energy conservation to ensure their longevity. The main challenge in managing this tradeoff is the inability of interfering BANs to explicitly coordinate their transmissions. This may result in unacceptably high battery energy draining rates to overcome cross-interference by other BANs in the vicinity. Here, we propose a utility-based, link-layer adaptation framework for balancing these tradeoffs for each BAN as well as across different BANs. The framework accounts for the utility of the BANs data rates and penalties associated with high transmission powers. Our analysis indicates that link-layer adaptation is beneficial for mitigating the interference from multiple adjacent BANs. Simulation results support our mathematical framework, indicating a much better spectral efficiency obtainable by using link layer adaptation techniques.

Keywords—body area network, reliability, link-layer adaptation

I. INTRODUCTION

Wireless Body-Area-Networks (BANs) are envisioned to provide short range, reliable communication for multiple wearable or implantable devices in close proximity or inside the human body [1]. While interference within each BAN can be effectively eliminated through coordination, e.g., using TDMA, external interference from other nearby networks, including BANs, presents a major challenge. However, the medical nature of BANs applications could impose stringent constraints on the reliability of its operations. Also, since BANs are mostly battery-powered, the requirement for reliable communication must meet the need for conserving battery energy.

This paper proposes a utility-based, link-layer adaptation framework, which has been successfully used for trade-off optimization in cellular and mobile ad-hoc wireless networks [2]. In the context of interfering BANs, this framework characterizes the performance of each BAN by its utility. This utility is defined as the difference between the communication utility (based on the data rate) and a penalty which is dependent on the transmission power. The overall system performance is characterized by the aggregate utility, which is the sum of the individual BAN utilities. This framework results in a fair resource allocation with resources being the effective data rate and battery energy.

In the case of negligible inter-BAN interference, the system utility maximization decomposes into maximization of individual BAN utilities. However, when the inter-BAN interference is significant, conventional optimization techniques might require explicit coordination between BANs. Here we consider a greedy optimization, which does not require explicit inter-BAN coordination. In this optimization “selfish” BANs independently maximize their individual utilities, given the experienced Signal to Noise plus Interference Ratios (SNIRs). We demonstrate that greedy power control may result in undesirable system equilibrium with some BANs being completely shut down due to high interference. However, a combination of power control with link-layer adaptation results in system equilibrium with all BANs being operational in harsher environments. BANs which have sufficient battery energy level to overcome external interference are capable of achieving required data rate. If such BANs are “too aggressive” i.e. trying to maintain their data rates by increasing transmission powers, then other BANs with insufficient battery energy levels may not be able to achieve reliable data communication with minimum acceptable data rates.

The paper is organized as follows. Section II describes a communication model of the interfering BANs. Section III introduces a utility-based system performance model. Theoretical limits on the system performance obtained through utility maximization are discussed in Section IV. Section V discusses greedy BAN adaptation, which does not require explicit inter-BAN coordination. Simulations results are provided in section VI. Finally, Section VII briefly summarizes our results and outlines possible directions for future research.

II. SYSTEM MODEL

Consider a system comprised of N BANs. For simplicity we assume that each BAN consists of one transmitter and one receiver node (i.e. one communication link). The extension of the mathematical analysis provided here to the case of multiple communication links is straightforward but it is omitted for brevity. We assume that the communication link in each BAN $i = 1, \dots, N$ has data rate r_i , which is a function of the corresponding Signal to Noise plus Interference Ratio $SNIR_i$, and the adaptable link-layer parameter g_i [3]:

$$r_i = \psi(SNIR_i, g_i), \quad (1)$$

where function $\psi(\cdot)$ depends on the uncontrolled BAN i parameters, e.g., packet structure. In (1)

$$SNIR_i = p_i \xi_{ii} / (\sigma_i^2 + I_i), \quad (2)$$

where p_i is the transmission power for BAN i , σ_i^2 is the noise power at BAN i , interference experienced by BAN i from other BANs $j \neq i$ is

$$I_i = \sum_{j \neq i} p_j \xi_{ji} \quad (3)$$

ξ_{ji} in equation (3) denotes channel gain from the transmitter in BAN j to the receiver in BAN i .

In this paper we consider BAN communication, using Direct Sequence Code Division Multiple Access DS-CDMA with the following threshold-based rate functions:

$$r_i = \begin{cases} R_i / g_i & \text{if } g_i p_i \xi_{ii} > (\sigma_i^2 + \sum_{j \neq i} p_j \xi_{ji}) \gamma_i \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

where parameter R_i represents the chip rate, and γ_i is the minimum required $SNIR_i$. This threshold-based model is amendable to theoretical analysis using Perron-Frobenius theory [4].

III. SYSTEM PERFORMANCE METRICS

Each BAN i can increase its data rate (1) by increasing its transmission power p_i . However, the desire for battery energy conservation could create a tradeoff between competing requirements of maintaining a minimum desired data rate r_i and higher transmission powers p_i when interference is high. This tradeoff can be quantified by introducing a BAN utility function associated with its data rate and a penalty function associated with its battery draining rate. We assume that BAN i utility of having data rate r is an increasing function of r i.e. $v_i(r)$. A popular choice is the following α -fair utility function [6]

$$v_i(r) = \begin{cases} w_i r^{1-\alpha} / (1-\alpha) & \text{if } \alpha \neq 1 \\ A_i \log r & \text{if } \alpha = 1 \end{cases} \quad (5)$$

where $w_i, \alpha > 0$ are constants. When $w_i = 1$, cases $\alpha = 0$, $\alpha = 1$, and $\alpha \rightarrow \infty$ correspond respectively to the allocations which achieve maximum rate, proportionally fair, and max-min fair. Since BANs are expected to guarantee certain data rate for critical medical data, it is natural to assume that data rate utility is close to max-min fair:

$$v_i(r) = -(r_i^{\min} / r)^{\alpha-1} \quad (6)$$

where $\alpha \gg 1$, and $r_i^{\min} := [w_i / (\alpha - 1)]^{1/(\alpha-1)}$.

We characterize BAN i performance by utility function

$$U_i = v_i(r_i) - h_i(p_i) \quad (7)$$

where increasing and convex function $h_i(p)$ characterizes penalty for draining battery energy. Given remaining battery energy E_i and target remaining battery life-span T_i , one can quantify penalty function $h_i(p)$ as follows. Hard constraint on the actual remaining battery life-span τ_i for BAN i , $\tau_i \geq T_i$ can be enforced by imposing hard constraints on the battery draining rate $p_i \leq E_i / T_i$. The “soft” version of this BAN longevity requirement allows for (a) mitigating increase in interference by temporary increasing transmission power above E_i / T_i and (b) creating “safety margin” by reducing transmission power below E_i / T_i if condition permits.

This soft version can be obtained by quantifying penalty for actual remaining battery life τ_i to be short of T_i by increasing function $\eta_i(T_i / \tau_i)$. Then, assuming constant transmission power p until battery energy depletion, we obtain the following penalty function $h_i(p) = \eta_i(pT_i / E_i)$. In the particular case of function $\eta_i(x) = B_i x^{\beta_i}$ with constants $B_i > 0$ and $\beta_i \gg 1$, the penalty function becomes:

$$h_i(p) = B_i (pT_i / E_i)^{\beta_i} \quad (8)$$

Note that increasing and convex function (8) is almost zero for $p < E_i / T_i$, and rapidly increases for $p > E_i / T_i$.

The overall system performance can be characterized by the aggregate utility, which is the sum of the utilities of individual BANs:

$$U := \sum_i U_i \quad (9)$$

Substituting (4) into (7) allows us to express BAN i utility in terms of BAN i link processing gain g_i and transmission powers of all BANs $p = (p_i)$:

$$U_i(p, g_i) = u_i(p, g_i) - h_i(p_i) \quad (10)$$

where

$$u_i = \begin{cases} v_i(R_i / g_i) & \text{if } g_i p_i \xi_{ii} > \left(\sigma_i^2 + \sum_{j \neq i} p_j \xi_{ji} \right) \gamma_i \\ v_i(0) & \text{otherwise} \end{cases} \quad (11)$$

Substituting (10) into (9) we obtain the following expression for the system aggregate utility as a function of the vectors of link processing gains $\mathbf{g} = (\mathbf{g}_i)$ and transmission powers $\mathbf{p} = (\mathbf{p}_i)$:

$$U(\mathbf{p}, \mathbf{g}) = \sum_i [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)] \quad (12)$$

IV. BOUNDS ON THE SYSTEM PERFORMANCE

Consider the following three BAN management frameworks: (1) power $\mathbf{p} = (\mathbf{p}_i)$ control only, (2) processing gain $\mathbf{g} = (\mathbf{g}_i)$ control only, and finally, (3) both power and processing gain control. The upper bounds on the system performance, achievable with these three frameworks, are given by solutions to the following three optimization problems:

$$\max_{\mathbf{p}} \sum_i [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)], \quad (13)$$

for power control only,

$$\max_{\mathbf{g}} \sum_i [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)], \quad (14)$$

for processing gain control only, and finally

$$\max_{\mathbf{p}, \mathbf{g}} \sum_i [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)] \quad (15)$$

for both link processing gain and power control.

When link processing gains $\mathbf{g}_i$ are fixed, all BANs $i = 1, \dots, N$ have non-zero data rates $R_i/\mathbf{g}_i$ if and only if the following system of inequalities

$$p_i \xi_{ii} \geq (\sigma_i^2 + \sum_j p_j \xi_{ji}) \gamma_i / \mathbf{g}_i \quad (16)$$

has solutions $p_i \geq 0$, $i = 1, \dots, N$. The minimum transmission powers $p_i \geq 0$ satisfying (16) are uniquely determined by solution to the following linear system:

$$p_i \xi_{ii} = (\sigma_i^2 + \sum_j p_j \xi_{ji}) \gamma_i / \mathbf{g}_i \quad (17)$$

The necessary and sufficient conditions for existence of non-negative solution to (17) can be formulated in terms of the Perron-Frobenius (P-F) eigenvalue of non-negative matrix $A = (a_{ij})$ with elements $a_{ij} = (\gamma_i / \mathbf{g}_i) \xi_{ji}$, χ as follows [4].

Assuming that matrix $A = (a_{ij})$ is non-reducible, system (17) has solution $p_i \geq 0$ if and only if $\chi < 1$. Since the P-F eigenvalue $\chi = \chi(A)$ is an increasing function of the elements of matrix $A = (a_{ij})$, one may expect that for sufficiently large thresholds γ_i or sufficiently low link

processing gains $\mathbf{g}_i$ the P-F eigenvalue χ exceeds unity; and thus, at least one BAN is completely shut down. The above analysis demonstrates that power control alone cannot guarantee reliable BAN operation. It can be shown that similar conclusion can be derived for other media access protocols and coding schemes.

In the case of DS-CDMA, link-layer adaptation can be achieved by controlling link processing gain $\mathbf{g}_i$ [3]. It is easy to see that given transmission powers $\mathbf{p} = (\mathbf{p}_i)$, the optimal processing gain keeps the $SNIR_i$ just above the threshold γ_i :

$$\mathbf{g}_i = \mathbf{g}_i^* + \varepsilon, \quad (18)$$

where

$$\mathbf{g}_i^* = \gamma_i (\sigma_i^2 + \sum_j p_j \xi_{ji}) / p_i \xi_{ii} \quad (19)$$

and small $\varepsilon > 0$ provides “safety margin” to guard against unavoidable fluctuations in the noise plus interference. This processing gain selection ensures the positive data rate for the link in BAN i :

$$r_i^* \approx \frac{R_i}{\gamma_i} \frac{p_i \xi_{ii}}{\sigma_i^2 + \sum_j p_j \xi_{ji}} \quad (20)$$

Thus, processing gain adaptation (18)-(19) allows BANs to operate even under unfavorable conditions of high noise plus interference. A possibility of further system performance improvement by combining processing gain adaptation with power control is discussed in the next Section.

V. GREEDY POWER AND LINK-LAYER ADAPTATION

For each optimization framework (13)-(15) and given the experienced noise plus interference $\sigma_i^2 + I_i$, consider the corresponding greedy maximization of the individual utility of each BAN i as:

$$\max_{p_i} [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)], \quad (21)$$

for power control only,

$$\max_{\mathbf{g}_i} [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)], \quad (22)$$

for processing gain control only, and finally

$$\max_{p_i, \mathbf{g}_i} [u_i(\mathbf{p}, \mathbf{g}_i) - h_i(\mathbf{p}_i)] \quad (23)$$

for both processing gain and power control. Schemes (21)-(23) do not require explicit inter-BAN coordination, and thus are readily implementable. The question to be answered, however, is the loss in the overall system performance as measured by the system utility (12), resulting from the greedy optimization (21)-(23).

Greedy optimizations (21)-(23) can be naturally interpreted as non-cooperative games of interfering BANs

$i=1, \dots, N$ attempting to maximize their individual utilities (10) over controllable parameters, e.g. transmission powers p_i , processing gains g_i or both. Since the individual BAN utilities (10) are decoupled with respect to the processing gains g_i , there is no loss in the system utility (12) for greedy optimization (22) as compared to the system utility maximization (14). However, since the individual BAN utilities are generally coupled with respect to the transmission powers p_i through experienced interference, greedy optimizations (21) and (23) could result in loss in the system utility as compared to the system utility maximizations (13) and (15) respectively.

In the case of low inter-BAN interference, the performance loss is negligible. However, when several BANs are located in close proximity to each other, the inter-BAN interference and the resulting performance loss may be high. Using Perron-Frobenius theory, one can easily demonstrate that in a high interference scenario, greedy power control (21) typically results in transmission powers $p = (p_i)$ violating conditions (16) at least for some of the BAN(s). Analysis in the previous Section shows that these BAN(s) are completely shut down; and thus, greedy power control (21) results in unacceptable system performance. However, greedy processing gain adaptation (22) ensures non-zero data rates (20) for all BANs $i=1, \dots, N$, assuming that the processing gain can be changed continuously.

Consider greedy adaptation of both transmission powers and processing gains (23) and assume that processing gain adaptation occurs much faster than transmission power adaptation. Then, given transmission powers $p = (p_i)$, the processing gains reach equilibrium (18)-(19) ensuring data rates (20). The “slow” greedy adaptation of transmission powers follows fixed-point equations

$$p_i^{t+1} = \arg \max_{p_i} U_i(p_i, p_{-i}^t) \quad (24)$$

where BAN i utility is

$$U_i^*(p) = v_i \left(\frac{R_i}{\gamma_i} \frac{p_i \xi_{ii}}{\sigma_i^2 + \sum_{j \neq i} p_j \xi_{ji}} \right) - h_i(p_i) \quad (25)$$

and $p_{-i}^t = (p_j^t, j \neq i)$.

Adaptation (24)-(25) can be viewed as describing dynamics in a non-cooperative game of BANs $i=1, \dots, N$ where each BAN i attempts to maximize its utility (25) over its transmission power p_i [9]. This dynamics converges to a pure Nash equilibrium of $p^* = (p_i^*)$, where

$$p_i^* = \arg \max_{p_i} U_i^*(p_i, p_{-i}^*) \quad (26)$$

Loss in the system performance for this greedy joint power control and link-layer adaptation as compared to the system utility maximization (15) can be quantified by the corresponding Price of Anarchy (PoA) [10]:

$$PoA = \left(\frac{1}{\sum_i U_i^*(p^*)} \right) \max_p \sum_i U_i(p) \geq 1 \quad (27)$$

Since Nash equilibrium (26) may not be unique, definition (27) assumes the “worst case scenario” Nash equilibrium $p^* = (p_i^*)$ producing the minimal system utility.

Practical applicability of greedy joint power control and link-layer adaptation (18)-(19), (24)-(25) depends on whether $PoA \approx 1$ or $PoA \gg 1$. For brevity, here we conjecture applicability of this cross-layer adaptation at least in some practically important scenarios. To support this conjecture consider utility functions $v_i(\cdot)$ and penalty functions $h_i(\cdot)$ given by (6) and (8) respectively, with parameters $\alpha \gg \beta_i \gg 1$. This parameter selection indicates that each BAN i 's willingness to achieve data rate $r_i^{\min}$ takes priority over battery energy conservation. However, once data rate $r_i^{\min}$ is achieved, battery energy conservation takes priority over further data rate increase.

It is easy to verify that for this utility/penalty selection, adaptation (24)-(25) takes the following form:

$$p_i^{t+1} \xi_{ii} = \gamma_i \frac{r_i^{\min}}{R_i} \left(\sigma_i^2 + \sum_{j \neq i} p_j^t \xi_{ji} \right) \quad (28)$$

and adaptation (28) for $t \rightarrow \infty$ maximizes the system utility $U^*(p) = \sum_i U_i^*(p)$, where $U_i^*(p)$ are given by (25). Since in this practically relevant scenario there is no loss in system performance, i.e., $PoA = 1$, one may expect the same in similar scenarios $PoA \approx 1$.

VI. SIMULATION RESULTS

To demonstrate the effectiveness of link-adaption control in multi-BAN environments, we have set up a simulation platform that can emulate the cross-interference of several BANs that are in the vicinity of each other. For example, Figure 1 is showing a scenario where 10 BANs consisting of one coordinator and one sensor node (i.e. one communication link) are initially distributed around a circle in a room of the size 10x20 meters. The arrows show the direction of the BANs moving toward each other. As BANs get physically closer, the amount of interference will increase and this in turn will affect the quality of the communication link at each BAN. The channel models used in our platform are based on the Standard document [11]. The frequency of operation considered in the simulation is 2.36 GHz which is the newly FCC approved spectrum for wearable BAN at indoor environments [12]. Further details of our simulation platform have been omitted for brevity.

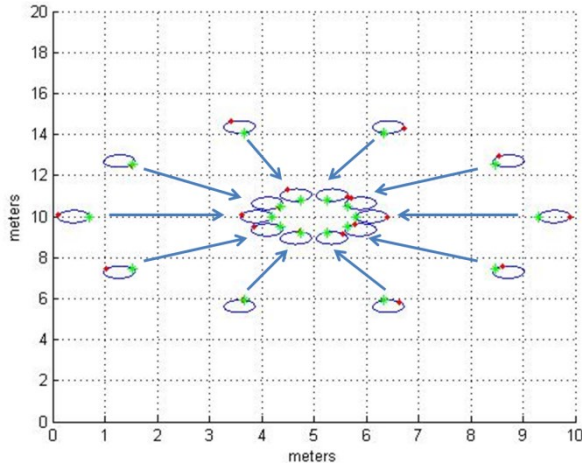


Figure 1. Sample multi-BAN scenario in a 10 m x 20 m rectangular room

Figure 2 highlights the aggregate rate achievable by the 10 BANs in Fig. 1 as they move toward each other i.e. interference increases. As observed the gain in spectral efficiency for the case of rate control (i.e. link adaptation) is higher when the BANs get closer to each other. Almost all simulated scenarios showed the same trend. The simulation platform is also capable of demonstrating this fact for the case of multi-link BANs, but those results are being omitted for brevity.

VII. CONCLUSION AND FUTURE RESEARCH

We have provided mathematical formulation of system utility maximization for balancing requirements of reliability and conserving battery energy in interfering BANs. System utility quantifies BANs “desire” for reliable communication and battery energy conservation. Balancing such tradeoffs generally require inter-BAN coordination due to cross-interference in multi-BAN environment. As inter-BAN coordination can be very complicated for many practical applications, we have discussed the performance of selfish BAN adaptation, which does not require such coordination.

Dynamic power and processing gain controls have been considered as alternatives for individual BANs to maintain reliable operation even in high interference environments. We have concluded that power control alone is insufficient to achieve an acceptable system performance. At the same time, optimal processing gain control alone (a) can be implemented without explicit inter-BAN coordination, and (b) significantly improves BAN performance as compared to the case of fixed processing gains. These conclusions are consistent with the results in [5,7,8]. We conjecture that joint power and processing gain control have potential to further improve system performance.

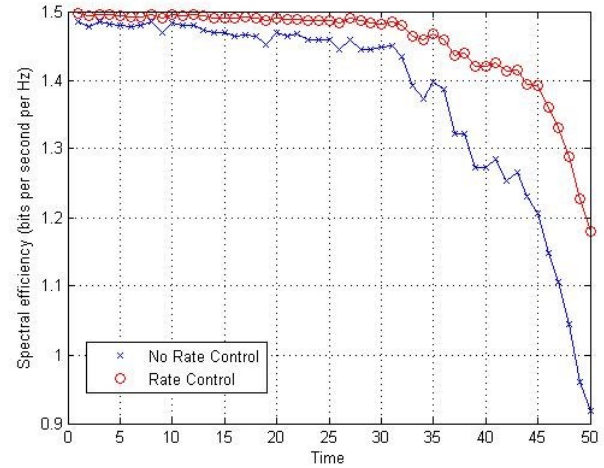


Figure 2. Averaged spectral efficiency for the multi-BAN scenario in Figure 1

Future research should include performance evaluation of the simple greedy adaptation algorithms analytically and through simulations. These algorithms should be compared to more sophisticated adaptation algorithms, which rely on implicit inter-BAN coordination through learning of multi-BAN interference pattern.

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