Designing Next-generation Implantable Wireless Telemetry

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Abstract: Biomedical applications in general, and health monitoring in particular, extensively involve on-body as well as implantable wireless communications devices to enable viable end-user solutions. While technologies to wirelessly transmit data from implanted devices have already been reported, they fall short of being able to support the needs of emerging next-generation biomedical applications. In order to translate state-of-the-art wireless technologies into solutions fitting body area network applications (BANs), a key challenge to overcome is the strictly limited power budget. This paper attempts to review design challenges and proposes a viable solution for wireless telemetry to meet the targets for next-generation BANs.

1 INTRODUCTION

A key to designing and implementing novel next-generation health care technologies lies in being able to seamlessly tap vital body parameters that help identify the cause of physiological anomalies. Mature state-of-the-art biomedical technologies utilize tethered devices. While these wired systems potentially enable interfaces between a living organism and an external machine for data analysis, wired transmission significantly hinders mobility and ease of use. The possibility of monitoring undistorted biological signals using an autonomous device with a low degree of invasivity forms the basis for exploring wireless communications for biomedical applications. Some of the specific applications for which these systems are targeted include brain-machine interfaces, cortical and retinal prostheses, amongst others.

Implantable electronics forms a vital component of the envisioned next-generation BANs using multi-implant communications. Such networks (Figure-1) would require implantable, multi-nodal communication systems that can offer safe as well as reliable communication between implantable nodes and external devices, enabling interoperability between different systems. Device autonomy, form factor and extended lifetime form key features of these potentially data-intensive communication applications. The design of a viable implant telemetry mandates intelligent use of the available resources, primarily power.

This paper reviews the current state-of-the-art technologies and limitations that pose challenges to designing viable solutions for next-generation wireless telemetry, together with the proposed methodology to devise a solution that can effectively conform to the power budgets for next-generation BANs. Section-II presents a brief review of state-of-the-art technologies used to design wireless telemetry for BANs and their shortfalls. Section-III elaborates the design challenges in devising solutions for next-generation BANs. Sections IV and V present our proposed methodology and approach to meet the projected power budgets for next-generation systems, respectively. A comparison of the projections based on our approach with existing wireless solu-

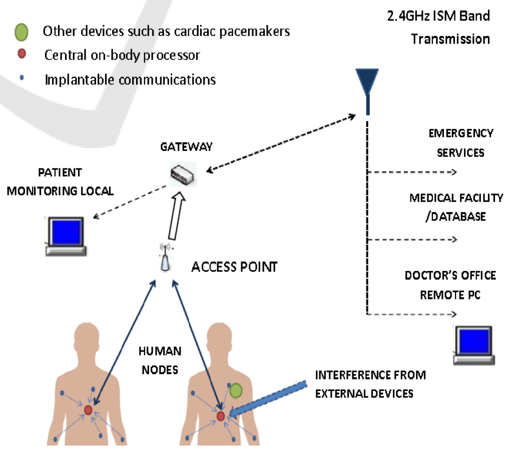

Figure 1: Envisioned next-generation Body Area Networks.

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tions for next-generation appears BANs in Section-IV followed by a conclusion in Section-VII.

2 STATE-OF-THE-ART

Implantable transmitters (TXs) are widely used for mature biomedical applications such as cardiac pacemakers, retinal and cortical prostheses, etc. However, the key differences between these applications and next-generation devices lie in the application requirements. While former applications require data rates in the order of kbps, future applications need data rates at least in the range of Mbps. Further, these applications address point-to-point communications involving single-channel links, where interference from other operational devices is low in a strictly interference limited regime. Novel systems and design approaches must support high data rate implant communications within the already stringent power budgets.

Existing technologies (Bluetooth (Group, 2002), Zigbee (Group, 2011), etc.) fail to provide a platform for reliable low-power communications between multiple implant sites, primarily due to the fact that power requirements for BAN devices can be no higher than a few tens of mW, and must support data rates on the order of kb/s to 100 Mb/s (Drude, 2007), while state-of-the-art technologies require power levels on the order of 20 mW to support data rates of a few tens of kb/s (one to two orders of magnitude too high). Thus, in order to translate state-of-the-art wireless technologies into modern BAN applications, a key challenge is to address these limited power budgets.

3 DESIGN CHALLENGES

The fundamental design challenge on the amount of available power is primarily limited by the safe temperature rise in tissue induced by the heat generated by an implantable device. Pennes bio-heat equation (Pennes, 1948) stipulates that the total heat accumulation in tissue is a cumulative effect of the thermal conduction, blood perfusion, radiation, circuit power consumption and metabolic heating. The allowable limit should accommodate both the required transmit power level and the total power consumption in the circuit, thereby implying that it is imperative to design highly efficient circuit components to target next-generation BAN applications, especially those with high data rate requirements. This upper bound on the total heat accumulation contributed by circuit power consumption is also critical in dictating the choice of the wireless communication scheme adopted for any given application. Typically to optimize power expenditure at the system level, higher modulation schemes such as Quadrature Amplitude Modulation (QAM) are generally avoided since their required circuit complexity deters an optimum implantable solution (J. Abouei and Pasupathy, 2011). Conventionally, modulation schemes such as Binary Phase-Shift Keying (BPSK), On-Off Keying (OOK) and Frequency-Shift Keying (FSK) have found widespread use in wireless implantable solutions requiring data rates up to a few Mbps, primarily due to their lower power requirements. The need for a more linear Power Amplifier (PA) pulls BPSK back in terms of power requirements, although BPSK is 3 dB better than OOK and FSK. Thus, since the choice of modulation scheme can be powerful in dictating the final architecture, and thus the power requirements, transceiver designs for implantable medical devices generally trade off spectral-efficiency for energy-efficiency.

Attempting to devise energy-efficient solutions close to upper bounds stipulated for BAN technologies at 500 pJ/bits (Drude, 2007) becomes ever more challenging due to device miniaturization towards desired rice-grain sized form factors. Fully implantable system for wireless telemetry additionally requires a signal acquisition unit, power source, implantable antenna as well as increased device functionalities. Further, link losses need to be minimized with the choice of frequency of transmission assuming significant importance. While conventional understanding teaches that transmission loss in tissue is minimized at lower frequencies, theoretical and experimental results in the 1-3 GHz band suggest that this band is a better (Poon, 2009), due to the fact that magnetic coupling for short distances of 1-5 cm for small antennas is strong with negligible dielectric polarization losses; contrary to E-M transmission modes.

To extend the life of an implanted device, it is important that a suitable mode of powering be selected based on the power requirements of the devised implant. The power source should be able to support the power requirements of the complete device, while ensuring an active device life of at least a few years. Implantable batteries are usually hardwired and sealed hermetically into the final device during the manufacturing process. The limitations of currently available battery technologies provide only limited amounts of power, while being large and bulky. Additionally, although a number of existing methods for energy harvesting can provide supplemental energy to the implantable batteries, thereby enhancing the useful life of the implant, given the power density offered by current technologies and the fact that most next-generation applications have significant power requirements, current harvesting technologies can only aid in relaxing a power requirements of the primary powering source rather than offering an autonomous solution (J. Olivo and Micheli, 2011). Inductive power links can be used, and most of the existing implant devices use inductive links with frequencies on the order of a few MHz or less, primarily due to the low absorption rates in tissues at these frequencies. The primary limitations of these conventional wireless powering technologies, however, are low efficiency and large form factor. Use of high-frequency inductive links allows a 100-fold reduction in the size of the implanted coil (Poon, 2009). However, high-frequency inductive links also suffer from low efficiency, in addition to high transmit power (A. S. Y. Poon and Meng, 2007). A critical issue in high-frequency inductive coils is the amount of power received at the implanted secondary coil. It has been shown that power on the order of a couple hundred μW can be provided ((Poon, 2009), (A. Yakovlev and Poon, 2012)), which can possibly be extended to sub-mW or mW ranges. Such power levels are safe for operation in tissue and and obey specific absorption rate (SAR) requirements. To power an implanted device with state-of-the-art high-frequency inductive links it is imperative to optimize the link. Designing an implantable wireless system within the limits of current technology therefore mandates a careful review of a number of factors: link power requirements, modulation, system and circuit design, and system operation.

4 PROPOSED METHODOLOGY

Transmission scenarios primarily dictate the topology of the complete link and the architectural design choices of required electronics and thus the design methodology. BAN applications target two primary transmission scenarios: (i) body surface, extending up to 2 cm above the skin, and (ii) external- up to 5 m (Chavez-Santiago et al., 2013). An evaluation of approximate link budgets for these topologies reveals a need for a two-pronged approach, wherein the first system would use magnetically coupled antennas while the second uses RF-based transmission. A key design objective is thus to enable reliable transmission with minimum energy requirements.

Use of spread spectrum signaling can not only aid to enhancing the reliability of the proposed implantable telemetry but can also help in supporting communication between multiple implantable nodes. Also, since transmissions in these applications are intermittent and erratic, a preamble-based detection system suits the application scenario. A low-complexity transmission architecture can further be supported by using the proposed asynchronous packet-based transmission system based on direct-sequence spread-spectrum modulation (S. Nagaraj and Burnashev, 2009) due to its inherent ability to reliably support uncoordinated data transmission with low power consumption. The basic modulation scheme is differential binary phase shift keying (DBPSK) in addition to spread spectrum. While DBPSK allows for a simple modulation with superior bit-error-rate (BER) performance as compared to low-complexity modulation schemes typically used in biomedical applications (such as on-off keying, frequency shift keying etc.), the use of spread spectrum signaling offers system reliability due to inherent robustness to interference and multipath propagation, in addition to enabling scalability to support multi-implant communications. The proposed scheme embeds the transmit data into a packet structure marked with a preamble sequence, which when detected by the receiver can be used to extract timing information for synchronization. This allows for reduced power consumption since it alleviates the need for continuously operating a synchronization stage, otherwise typically used in conventional spread spectrum systems. Additionally, it has been shown in (S. Nagaraj and Burnashev, 2009) that due to differential encoding, the proposed preamble detection method does not require phase and frequency offset estimates for channel coherence time larger than the block duration, thereby, contributing to a significant reduction in system complexity. Also, without the need for exact timing information, a detector operating with two samples per chip essentially performs close to that of a synchronous system and is robust in frequency-selective channels.

The design methodology is dictated primarily by the application scenario or link topology. In the case of body surface transmission, data transfer can typically be enabled without the need for high transmit power levels since the amount of loss encountered in the channel is low for small transmission distances. A first estimate of link losses at an implantation depth of 2 cm of tissue reveals that losses are about 20-30 dB less in the 2.4 GHz ISM transmission band as compared to the conventional understanding (N. R. Sarchoghaei and Schlegel, 2013). It is observed that to be able to support acceptable transmission using the proposed communication scheme, the energy required to transmit every data bit over 2 cm of tissue is about 64 fJ. Table-1 lists first hand worst-case estimates of energy requirements (using upper-bounds on loss margins) for data transmission through a proposed link for body surface transmission at an implantation depth of 2 cm at low kbps data rates. With such link topologies, energy requirements imply that optimization of the system design is dominated by the power consumption of the implantable electronics, and hence the need to aggressively reduce system complexity. A pair of inductive coils can be used to enable data transfer through magnetic coupling without overly burdening the power consumption of the embedded electronics. Furthermore, subthreshold design techniques can be applied to baseband electronics to significantly lower power consumption levels.

Table 1: Approximate link budgets for proposed transmission scheme to achieve P(miss)=10^{-6} + P(false)=10^{-3} in the 2.4 GHz ISM band; GA - Antenna Gain, RX - Receiver.

Link Parameters	**MI**	**RF**
Required $\frac{E_b}{N_o}$ (dB)	12	12
Receiver Noise Figure (dB)	3	3
Noise Power (dBm/Hz)	-140	-108
TX and RX GAs (dBi)	-	0
RX Sensitivity (dBm)	-128	-96
Implant depth (cm)	2	0.2-0.7
Tissue Path Loss (dB)	-30	-(7-17)
Free Space Path (m)	-	1-5
Free Space Path Loss (dB)	-	-(40-53)
Fade Margin + Excess Loss (in dB) (Merli, 2011)	-25	-2
Man-made Noise Margin (dB)	-	-25
Transmit Power (dBm)	-73	-22/1
Data Rate (kbps)	1.25	2000
Energy per bit (pJ/bit)	$\prec 0.1$	3-600

Data transmission to nodes external to implants located at 2 cm beyond skin surface is estimated to require significant transmit power levels to address the increased path loss encountered in such topologies. Hence, the proposal to use RF transmission, which requires antennas that generate both electrical and magnetic field components. A first estimate of link losses at an implantation depth of 0.2-0.7 cm of tissue and an over-the-air transmission up to 5 m shows that to be able to support acceptable transmission (Table-1) the energy required to transmit a data bit from the proposed implanted TX is 3-600 pJ and the required transmit power level is -22 to 1 dBm at 2 Mbps.

With the given definition of the BB section, upconversion of the BB signal in the RF TX calls for a suitable architecture requiring a phase-locked loop (PLL), voltage-controlled oscillator (VCO), mixer and power amplifier (PA). The primary design constraint stems from the efficiency of the PA. A linear PA theoretically offers an efficiency of 50%, while realistically achievable efficiencies are about 20-40%. Use of a non-linear PA is possible only when the signal has a constant envelope. This again points to a careful selection of the modulation scheme. Antenna efficiency and thus the choice of antenna also impacts the total power that can be transmitted. Thus, a critical design issue for the RF section is to balance device size, circuit power consumption and link efficiency.

While the basic system definition and adopted implementation architecture contributes to significant power-savings, implementation using shorter gate lengths with low-power techniques can further contribute to shrinkage in power consumption. Energy-efficiency (EE) can be further enhanced by using duty-cycled operation, and such systems can then be effectively operated near their high-efficiency modes.

5 FITTING POWER BUDGETS

The envisioned design roadmap towards viable low-power implantable wireless telemetry primarily requires adaptation of the basic design to shrink the fundamental power requirements, such that the device can be deemed fit for next-generation BANs. In an effort to design a viable energy-efficient implantable wireless telemetry system using our methodology, a previous first-generation prototype (GEN-I) included the implementation of the baseband section in IBMs 130 nm CMOS process with an EE of 1.2 nJ/bit. Gen-II implementation involves fabrication of both the baseband and the RF TX sections in Taiwan Semiconductor Microelectronic Corporationś (TSMCś) 65-nm technology. Experimental evaluation of fabricated Gen-II ICs is currently underway and is expected see completion by end-2013.

The estimated energy/bit requirements of the TX core in the BB section of the proposed wireless communications device for data transmission to 2 cm beyond body surface is about 118 pJ/bit for operation at nominal voltages in TSMCs 65nm CMOS technology. A comparison of the link budget with the energy requirements of the GEN-II prototype TX core, shows that the design is dominated by the circuit power consumption. However, it is observed from preliminary estimations of the proposed subthreshold implementation of the current TX design that in body surface transmission scenarios with low data rate requirements, circuit power would not form the primary bottleneck. However, a key design challenge to address is enhancement of the supportable data rate at a minimum threshold voltage. As shown in (Meinerzhagen et al., 2011), a suitable combination of implementation technology from among low-V_T, high-V_T and standard-V_T technologies together with a careful architectural revision can definitely help in achieving the targets. Therefore, with the target to devise a high-efficiency BB TX prototype at higher data rates, we plan to further explore subthreshold implementation for the next-generation prototype development for application in body surface transmission scenarios (Gen-III (a)) with a revision in the BB architecture.

For the case of an RF link for transmission to external nodes, the first-order estimates project that the power requirements of the baseband packet assembly and RF sections in the proposed implantable wireless telemetry in a standard TSMC 65 nm implementation (Gen-II) are about 1.5 mW each (energy efficiency 1.5 nJ/bit approx.) at 50MCps (data rate 3.125 Mbps) and the maximum transmit power rating of 0.2 dBm. The estimated energy/bit requirements of the proposed wireless communications device for data transmission to external nodes projects that power consumption can be progressively reduced over the next-generation prototypes. While a significant amount of energy reduction is achieved with implementation of the modified baseband TX in a smaller technology node, with the power requirements lowering to 88% of that for Gen-I (65% is attributed to the reduction of gate length and supply voltage), power requirements need to be aggressively scaled down further to make it comparable to the link budget of the given application. The proposed implementation roadmap targets design optimization as well as burst-mode operation to achieve the targeted allowable power consumption metrics for next-generation BANs. The energy savings in Gen-II can be further reduced in Gen-III(b) (to 1.2 nJ/bit) with architectural revision (control unit of BB) and optimization (PA efficiency 50%). To enable higher power savings, we propose to implement duty-cycled (50 %) in Gen-IV while progressing towards the final target stipulated for next-genartion BAN devices (Gen-V). Figure-2 presents the estimated energy/bit requirements of the proposed wireless communications device, projecting that power consumption can be progressively reduced over the next-generation prototypes using revised design approaches at both the gate and system levels.

Proposed targets for the BB design aim to achieve 10pJ/bit or less for all digital processing in final prototypes, implying that power budget of the implantable electronics will be dominated by the RF section, with system operation at the minimum required data rate. Thus, the RF circuitry is the next limiting factor after link requirements (Table-2). However, operation at higher transmit rates can significantly reduce the EE of RF TX. An increase in required transmit power levels (P_{TX}) increases with data rate but results in increasing overall EE of the telemetry system, thus implying that a fundamental increase in efficiency can be achieved by running the device at higher data rates. Hence, operation in burst-mode would enable two-fold energy savings conservation during sleep times and operation at high-efficiency transmission modes.

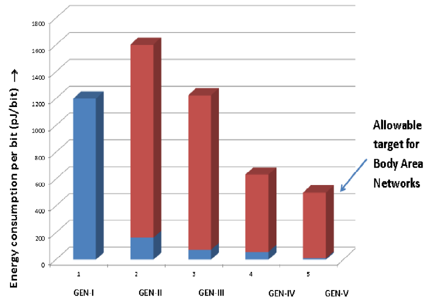

Figure 2: Proposed evolution of next-generation wireless communications IC energy consumption with respect to the allowable targets for BANs, with 0.2 dBm transmit power; Blue - Energy consumption of BB; Red - RF.

To better understand the advantage of supporting higher P_{TX} at high data rates, we also evaluated the power requirements and energy-efficiencies of the BB and RF TXs at a rate higher than allowable in the chosen band and at full P_{TX} of the RF TX (Table-2); a specific transmission scenario with the base station located at 2m from body surface is considered.

Table 2: Estimated energy requirements of the baseband and RF TXs (Gen-II) with different transmit rates to a distance of 2m in free-space.

Chip (Rate) (MCps)	P_{TX} **(dBm)**	**Link Budget (pJ/bit)**	**Gen-II EE-BB (pJ/bit)**	**Gen-II EE-RF (pJ/bit)**
132	0.2	127	110	545
83.5	-2	127	115	632
50	-4	127	119	844
41.8	-5	127	121	920
32	-6	127	124	1108

At a 132 MCps chip rate (full P_{TX}), EE of the RF section is significantly higher than that at the minimum required transmission rate. Thus, at the maximum rating, the transmit rates that can actually be supported would be higher, thereby reinforcing the proposed methodology that a burst-mode operation at a higher efficiency operating node would be the optimal solution to address the limitations posed by RF design. The next challenge is then to reduce the power requirements of both the BB and RF sections with detailed evaluation of both system-level architectures as well as gate-level implementations. It is observed that there is room for significant improvement in the EE of the BB section with a careful review of system architecture and intelligent delegation of system blocks that can remain external to the implantable device. In addition, our first-order estimates clearly suggest that burst-mode operation can further help improve EE.

6 DISCUSSION

In comparison with existing implementations of implantable wireless telemetry systems with comparable link topologies in the literature (Maush and Delgado-Rstituto, 2013), we conclude that our current (Gen-II) projections are competitive (Table-3). In comparison to recent TX prototypes with supportable data rates greater than 1 Mbps, our proposed TX design has a higher efficiency. A careful review of the existing systems also shows that although the proposed TX falls short of some existing TXs in terms of the efficiency, the former fall behind in terms of supportable data rates and have low link budgets.

Table 3: Comparison of energy per bit requirements of proposed implantable wireless device with recent implantable solutions; η - TX efficiency and R_b-Data rate (Mbps).

Design	**Link Budget (pJ/bit)**	R_b	**Energy per bit (pJ/bit)**	**TX η (%)**
Solda11	14	5	200	7.1
Gambini12	3.4	1	30	11.3
Vidojkov11	68	10	400	17.1
Ayers10	191	1	950	20.1
D'Fabbro10	1050	1	10^4	10.5
Mausch13	1470	1	6000	24.5
This Work	127	3.125	963	13.2

Thus the next step is to optimize the PA efficiency as well as reduce the power consumption of the mixer+VCO unit together with optimization of the BB architecture such that the EE at high transmit rates do not remain bottlenecks in the realization of the next-generation implantable wireless telemetry solutions. Once the basic design of a single-terminal communication system is established based on asynchronous packet transmission, the inherent advantage of the proposed system to support multi-terminal communications using signature spreading sequences will be explored. The envisioned system design issues, primarily those regarding link topology and channel distortions, need to be further investigated in-depth, both theoretically and experimentally.

7 CONCLUSIONS

Power budgets stipulated for safe operation of highly miniaturized implantable devices to be used in next-generation BANs are stringent. In addition, the challenges to target high data rates and longer operational life using devices with small form factors contribute to the need for novel system architectures and design approaches. While the proposed packet-based transmission system can offer a solution to effectively address power usage limitations, the reliability of such devices needs to be further investigated.

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