Institute for Digital Communications

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Research Internship/Major Project/Master Thesis

Optimizing the Placement of IoBNT THz Interface Devices in the Cardiovascular System under Sensing and Tissue-Fading Constraints

The Internet of Bio-Nano Things (IoBNT): As an extension of the Internet of Things (IoT), the *IoBNT* envisions the human body as an additional communication domain beyond everyday connected devices. The IoBNT opens the door to innovative medical applications such as real-time health monitoring and personalized medicine [1]. To realize this vision, the IoBNT integrates in-body molecular communication (MC) systems with out-of-body electromagnetic wave (EM)-based communication networks, as illustrated in Fig. 1. Sensing and actuation within the body, e.g., within the cardiovascular system, as well as signal conversion between the EM and MC domains are performed by nano- to microscale devices known as *interfaces*. However, several key questions regarding these interfaces remain open.

Research Question: In particular, the **optimal placement of interfaces within the body to support biomarker-based health monitoring and efficient communication with external systems** is still an unresolved challenge. This project aims to address this by integrating insights from molecular transport modeling, tissue fading analysis, and terahertz (THz) communication testbeds to derive well-founded recommendations for ideal interface locations within the body.

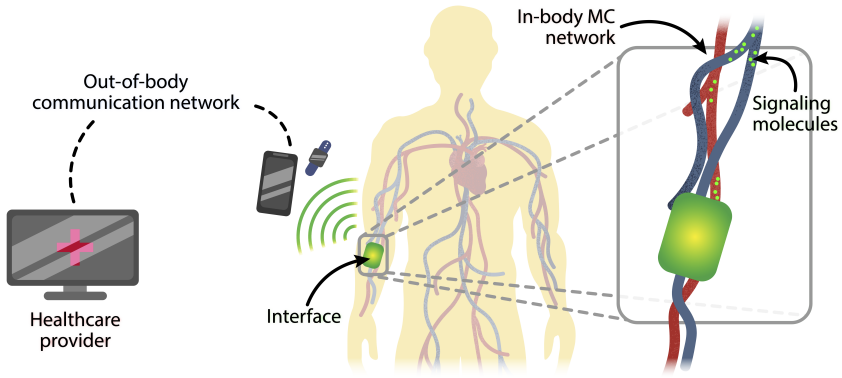
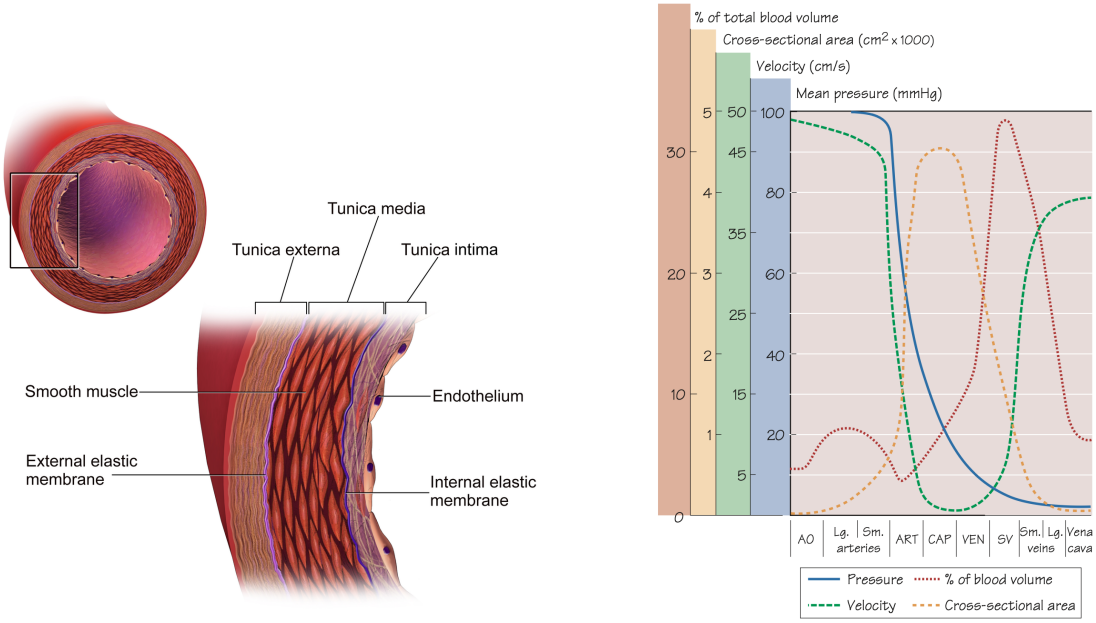


Figure 1: The IoBNT. In-body MC networks are connected bi-directionally to out-of-body EM-based communication systems via an interface, e.g., to enable in-body health-monitoring.

Physiological Interface Placement Considerations: Assuming stationary interfaces, i.e., devices fixed in place, their positioning within the body could, in principle, span various tissue types. However, due to the exceptional biomarker richness of the bloodstream [2], we focus on interface placement in close proximity to, or directly at, blood vessel walls, cf. Fig. 2a. Consequently, the interface placement task becomes the task of selecting the most suitable blood vessels for biomarker sensing. Two major considerations are made:

- **C1 Sensitivity constraint:** Interfaces require biomarker concentrations to exceed a minimum threshold to generate meaningful measurements. Hence, ideal vessels are those with high volumetric blood flux, which increases the likelihood of sufficient biomarker delivery to the sensing site. Volumetric blood flux strongly varies throughout the body [2], cf. Fig. 2b.
- **C2 Sampling rate constraint:** Depending on the sensing mechanism, interfaces may support only limited sampling rates. Therefore, target vessels should exhibit sufficiently



(a) Structure of an artery wall.

(b) Hemodynamic properties across blood vessel types in the human body.

Figure 2: Physiological considerations for IoBNT interface placement include hemodynamic factors and tissue types.

low flow velocities to enable effective temporal sampling of the passing biomarkers. Blood flow velocity strongly varies throughout the body [2], cf. Fig. 2b.

To support the proposed project, several models for biomarker propagation in networks of medium-sized arteries have been developed at IDC that allow for the prediction of blood flow rates and spatiotemporal biomarker concentration [3, 4].

THz Interfaces: To date, a multitude of (uni- and bi-directional) interface designs have been proposed and partially validated in lab environments, relying on different signal modalities, including optical [5, 6], magnetic [7], chemical [8, 6, 9, 10], acoustic, and temperature-based signals [11]. One contender for the realization of the IoBNT are THz-based interfaces [9], that establish a link between the in-body MC system and the out-of-body domain using EM waves at carrier frequencies of around 0.1 THz to several hundred THz. The THz band offers several distinct advantages in the context of the IoBNT:

1. THz wavelengths (roughly 1 µm to 1 mm) match the dimensions of nano- and microscale antennas (e.g., graphene-based plasmonic antennas).
2. THz waves interact strongly with vibrational and rotational modes of biomolecules and water clusters [12]. This enables molecular fingerprinting, which can directly detect biomarker concentration changes.
3. Compared to optical or near-infrared waves, THz radiation can penetrate a few millimeters into soft tissue, allowing near-surface external coupling (e.g., through skin or vascular walls) without requiring invasive wiring.

At the same time, the use of THz frequencies in the IoBNT entails several challenges:

C3 THz signal generation constraint: Producing THz signals remains technologically demanding, particularly at the nano- and microscale. Consequently, *passive* interface designs, in which an external THz wave is reflected and modulated by in-body MC processes, are currently considered more promising than *active* designs that generate THz signals internally. This limitation is further compounded by the restricted energy resources available to in-body nano-devices.

C4 Tissue fading constraint: THz waves experience strong attenuation in biological tissue [12]. As a result, even at practical transmit powers on the order of 1 mW, reliable communication can likely only be maintained over distances of a few millimeters.

C5 Dynamic environment constraint: The in-body THz propagation environment is highly dynamic and heterogeneous. Variations in tissue composition, blood flow, and physiological motion continuously affect the dielectric properties of the medium, leading to time-varying channel conditions and posing additional challenges for stable communication.

Tissue Fading Models and Self-Healing Beams: To enable link budget analysis of THz communication through biological tissue, several tissue fading models have been proposed [12, 13, 14, 15]. Three major signal losses have been identified:

1. **Absorption loss:** Caused by the strong interaction of THz waves with water molecules and biomolecular vibrations, leading to significant energy dissipation as heat.
2. **Spreading loss:** Results from the geometric divergence of the THz wavefront as it propagates through tissue, reducing the received power with distance.
3. **Scattering loss:** Arises from microscopic inhomogeneities in biological tissue, such as cells and organelles, which cause random deflection and diffusion of the THz signal.

While the absorption and scattering loss are imposed by the environment and cannot be avoided, the impact of spreading loss can typically be reduced by beamforming techniques. Lately, so-called *self-healing beams* that can maintain their core intensity profile over longer distances compared to Gaussian beams, and partially reconstruct after encountering small obstacles (e.g., blood cells), have been proposed as a possible solution for the problem at hand. One example for such beams are Bessel beams [16].

Optimal Interface Placement: To derive recommendations for ideal interface locations in within the body, we will focus on a selection of the physiological constraints C1 and C2, as well as THz-related constraints C3 and C4.

Potential Work Packages The project is divided into the following work packages (WPs), which are intended to provide flexibility. **Not all WPs must be completed; rather, the student is encouraged to explore those that best match their background and strengths.**

WP1 The design of a THz-based, bi-directional, and passive implanted IoBNT interface device shall be conceptualized. The capabilities of the interface lay the foundation for further WPs.

WP2 Using existing models for blood flow and biomarker distribution[3, 4], promising interface locations that optimize constraints C1 and C2 shall be identified.

WP3 Based on existing tissue-fading models [12, 13, 14, 15], a novel model incorporating the potential reduction of spreading loss through the use of self-healing THz beams shall be derived [16].

WP4 Link-budget predictions made by the developed tissue-fading model shall be validated through COMSOL simulations.

WP5 Exploiting the developed tissue-fading model, concrete recommendations about the feasible communication distance through various kinds of biological tissue shall be derived under constraints C3 and C4.

WP6 Recommendations resulting from C1 and C2 shall be integrated with those from C3 and C4, ultimately yielding estimates for the ideal interface locations in the human body.

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Start date: TBA
End date: TBA

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