

## **A Comparison of Waveforms for High-Accuracy Localization of Implantable Biomedical Sensors**

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Research on implantable biomedical radio-frequency sensors has gained traction in the scientific community due to the array of potential applications, such as, the detection of cancerous tumors, drug delivery, wireless capsule endoscopy (WCE), brain mapping, robotic surgeries, etc. The sensors are submillimeter capsules with two distinct categories of application: stationary units that can localize cancerous tumors, especially non-palpable breast lesions, or that are mobile units and can move within the body for applications like biopsy, WCE, microsurgery or drug delivery systems. One of the fundamental challenges for the mobile bio-sensor applications is being able to localize and track the sensors with high precision. Earlier works on preoperative wireless localization of cancerous tumors studied use of audio frequency sensors to locate the radio-frequency identification tags up to an accuracy of  $\sim 1$  cm (e.g. Reicher, et al., *American Journal of Roentgenology*, vol. 191, 2008, and, Almalki, et al., *The Breast*, vol. 69, 2023). Recent studies have demonstrated the use of low-frequency (125–134 kHz) for localizing passive tags within  $\sim 10$  mm range (Joo et al., *Surgical Endoscopy*, vol. 33, 2019).

Recently, ultra-wideband (UWB) continuous wave radio frequencies have been increasingly used to achieve localization. In Ray et al, *IEEE Transactions on Biomedical Circuits and Systems*, vol. 17, 2023, the authors were able to localize with an accuracy of  $\sim 5$  mm with the design of transceivers that are integrated with the circuits. On the other hand recent studies have shown the efficacy of using UWB radar-on-chip technology for cardiovascular imaging due to its sub-millimeter motion tracking capabilities (e.g. Lauteslager et al, *IEEE Trans. on Biomed. Eng.*, vol. 69, 2022). However, UWB signals require significant hardware resources in terms of bandwidth and power, resulting in transceiver and signal processing complexity, and are susceptible to reflections, especially in heterogeneous media.

In this work, we compare waveform designs and their effectiveness for localization in the human body using full-wave numerical simulations for different in-situ biomedical sensor applications. The main goal of this study is to determine the trade-off between ranging bandwidth (including spectral occupancy) and maximizing the localization accuracy. We investigate the effects of waveform bandwidth on the accuracy and precision of localization of a moving biomedical sensor by gradually decreasing the bandwidth from 30 % of the carrier frequency of 2.1 GHz to a narrow bandwidth of 40 MHz. We explore the efficacy of various ranging waveforms. Our analysis includes comparing the spectrally sparse two-tone waveform for ranging against the well known linear frequency modulated (LFM) waveform. We then investigate the effects the dual-LFM waveform detailed in Bhattacharyya et al., *20th EuRAD Conf.*, 2023, on range resolution.