Pulse Harmonia: Decimeter-Scale Tracking of Small Indoor Objects

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ABSTRACT

We present Pulse Harmonia, a real-time RF localization system which targets mass- and power-constrained mobile robotics systems. Pulse Harmonia is an ultra-wideband location system which achieves decimeter-level accuracy built using only commodity components. Pulse Harmonia tags transmit ultra-wideband pulses using the step recovery effect of common RF BJT transistors therefore making them inexpensive ($4.28), low-power (70 mW), and lightweight (3.3 g). Fixed-location anchors use a novel ultra-wideband band-stitching technique to recover high-resolution impulse response measurements using a traditional narrowband architectural approach. In complex indoor environments, Pulse Harmonia captures 56 location estimates per second with an average accuracy of 34 cm and 4.7 cm of inter-sample noise. Location estimation processing is performed in real-time and the resulting location estimates are provided for use in tracking or visualization purposes.

1. OVERVIEW

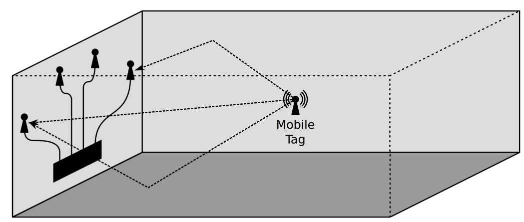
The Pulse Harmonia localization system consists of transmit-only tags and a fixed-location anchor infrastructure. Figure 1 shows the top-level system diagram and block-level diagrams for the transmit-only tags and receive-only anchors. Pulse Harmonia tags transmit repeating ultra-wideband pulses, while the anchors listen to determine the transmission's time-of-arrival for use in time-based location methods.

1.1 Ultra-Wideband Transmission

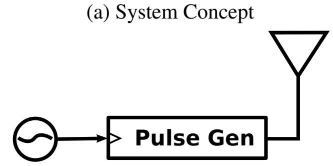
The widespread proliferation of ultra-wideband transmission has historically been hindered by the complexity of custom silicon, the use of rare RF components such as step recovery diodes, or the layout of complex microstrip geometries. Designs utilizing the step recovery effect of common RF BJTs have shown the best performance in power and cost, yet still require detailed knowledge of RF layout to create microstrip line differentiators [3]. The Pulse Harmonia tag design shows that further simplicity can be gained through removal of the microstrip differentiator without loss of performance.

1.2 Ultra-Wideband Bandstitching

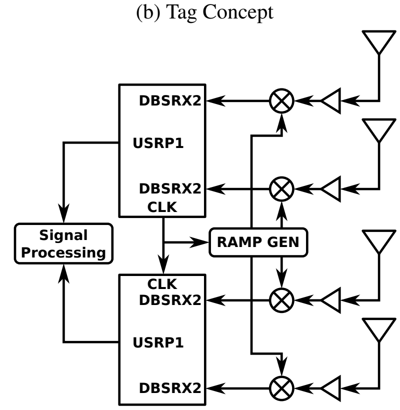
The RF propagation channel is typically very cluttered in indoor environments, resulting in many propagation paths between tag and anchor. It is therefore necessary to distinguish the time-of-arrival of the line-of-sight path from other propagation paths that follow closely behind. A direct correlation between the amount of utilized bandwidth and the resolution of the derived impulse response necessitates the use of an ultra-wideband receiver for accurate



(a) System Concept



(b) Tag Concept



(c) Anchor Concept

Figure 1: Overall system architecture for the Pulse Harmonia location system. (a) A mobile tag in free space broadcasts a UWB signal that is captured by anchor nodes. At least four fixed-location anchors are required to perform localization via multilateration. (b) The mobile tag design is expressly simple, acting as a transmit-only UWB pulse generator. (c) The anchors share a common clock source and sweep the UWB spectrum synchronously, capturing the entire signal generated by the tag using band-stitching.

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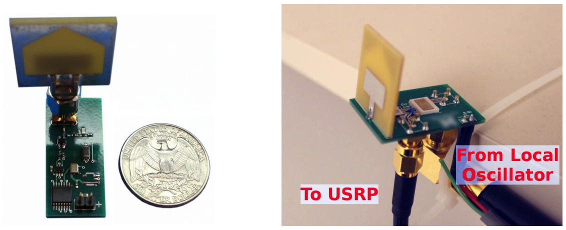

(a) Tag (b) Anchor

Figure 2: Pulse Harmonia tag and anchors. Tags measure 1.4 cm x 3.3 cm and contain pulse generation circuitry. Anchors consist of a centralized local oscillator frequency generator and separate RF front-ends for down-converting and digitizing the received pulse signals measured at each anchor.

time-of-arrival estimation. Contrary to the traditional use of costly high-speed ADCs or uncommon RF components such as sampling mixers, Pulse Harmonia anchors observe the ultra-wideband impulse response with a frequency-swept narrowband receiver design.

The frequency-swept design allows for an analysis of the received signal's characteristics in the frequency domain, allowing the Fourier coefficients of the received signal to be derived. Once the amplitude and phase of each Fourier coefficient is known across a 1 GHz bandwidth, Pulse Harmonia performs Fourier inversion to calculate the observed channel impulse response. The time-of-arrival is then derived by inspection from this calculated impulse response. Lastly, once time-of-arrival information is known at each anchor, the tag's position is estimated using a time difference-of-arrival technique (TDoA). These band-stitching techniques were first utilized extensively in the WASP system [5], and we demonstrated their extension to the ultra-wideband case with Harmonia in HotWireless '14 [4].

1.3 Centralized Location Estimation

All location operations are performed in real-time with a dedicated PC. First, a software-defined radio (SDR) at each anchor digitizes and communicates the baseband data to a central PC. From there, a GNURadio flow graph processes the incoming data to calculate position estimates in real-time.

Signal processing operations start with estimation of the pulse repetition frequency. Once the pulse repetition frequency is known, the Fourier coefficients across the entire frequency sweep are obtained through direct manipulation of the baseband data from each anchor. By performing a deconvolution step, the processing framework obtains estimates of the channel impulse response at each anchor. Through analysis of the channel impulse response, estimates of the time-of-arrival for the line-of-sight path are derived. Lastly, time differences in arrival between anchors are used to derive an estimate of the tag's location.

2. ENTRY DETAILS

The Pulse Harmonia system hardware pictured in Figure 2 consists of custom tag and anchor hardware. Pulse Harmonia tag hardware consists of an RF BJT pulse generator triggered by a 4 MHz oscillator to govern the tag's pulse repetition frequency. The tag's basic design is modeled off of previous work [3]. In contrast to this previous work, the design has been simplified by removing the differentiator microstrip as it was deemed unnecessary to generate adequate RF power in the bandwidth of interest (3-4 GHz). Figure 3 shows the schematic for the new tag design.

Pulse Harmonia anchors use a shared frequency-swept local oscillator (LO) signal to sweep each anchor across the entire bandwidth

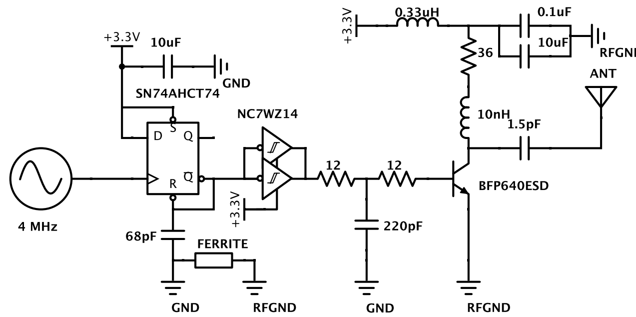

Figure 3: Tag circuit diagram showing the interconnection between the oscillator, monoflop generator, and BJT transistor. Additional passives are necessary for pulse shaping functionality. Total tag cost in large-quantity prices comes to approximately $4.28 per tag.

of interest. The custom sweep generator design is simplified by the ramp generation functionality built into the ADF4159 chip. After downconversion, the intermediate frequency (IF) signal is brought back to a USRP1 [1] software defined radio with a DBSRX2 daughterboard. After digitization internal to the USRP1, the baseband data is communicated to a central PC for signal processing, localization, and visualization tasks. All UWB antennas are built using a proven small form-factor design using traditional FR4 substrate [2].

3. MATERIALS AND SETUP

The Pulse Harmonia location system is infrastructure-based and has certain requirements for system setup. Anchors are placed throughout the environment and connected via coaxial cable to the centralized radio receivers. The centralized radio receivers and data processing station has AC power requirements for operation. Real-time location estimates will be locally visualized on a web-based 3D display. The tags are battery-powered and only need be affixed or placed on the object under surveillance.

4. REFERENCES

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