IBSync: Intra-body Synchronization of Wearable Devices Using Artificial ECG Landmarks

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ABSTRACT

The synchronization of wearable devices in distributed, multi-device systems is a persistent challenge. Particularly machine learning approaches suffer from the devices' inaccurate clock sources and unmatched time. While the online synchronization based on radio transmission is energy-intensive, offline approaches originated in activity recognition suffer from inaccurate motion patterns. In recent years, intra-body communication emerged as a promising technique that uses the human body as a limited and hence more efficient medium. Due to the absence of commercial platforms, applications are rare and underinvestigated. To boost their development and to enable the precise synchronization, we introduce *IBSync* and propose to repurpose the ECG sensor in commercial wearable devices to detect artificial signals induced into the skin. The short-time Fourier transform and Pearson's normalized cross-correlation are used to detect, precisely locate, and assign synchronization landmarks within the measurements. Based on a total of 105 min of recordings, we evaluated the concept and demonstrate its general feasibility with a promising accuracy of 0.203 ± 1.633 samples (1.587 ± 12.755 ms) in typical proximity to the transmitter.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile devices**; • **Hardware** → *Digital signal processing*.

KEYWORDS

synchronization; intra-body communication; multi-device sensing; electrocardiography; wearable devices

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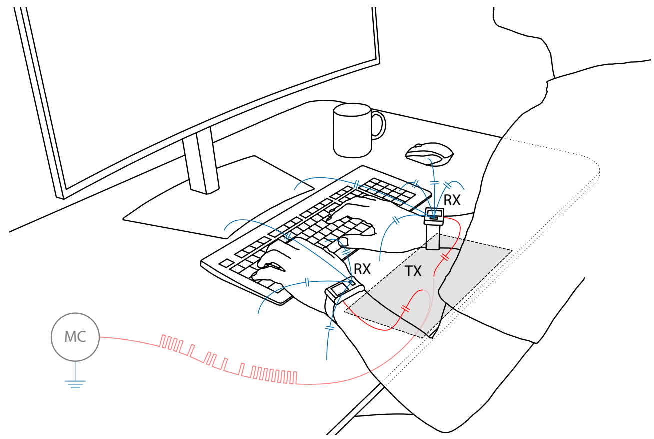

Figure 1: Exemplary scenario of *IBSync*: microcontroller (MC) with transmitter electrode (TX) embedded into a desktop, implicitly and incidentally synchronizing two sensing devices (RX) worn at the wrists, receiving artificial landmarks (red), capacitively induced into the human body. Detection by means of repurposed analog ECG sensor frontends. Weak return paths (blue) via environmental ground.

1 INTRODUCTION

Over the last two decades, numerous wearable devices entered the market targeting the wearer's continuous ambulatory and non-invasive monitoring. The synchronization of such devices' autonomous clocks in distributed, multi-device systems is, however, still a persistent challenge. The application of traditional signal processing but especially of cutting-edge machine learning approaches hence suffers from inaccuracies and unmatched time [39, 50]. Nevertheless, most commercial devices do not provide the option to synchronize online, during operation. Moreover, available methods based on wireless communication, of which Bluetooth is the most popular one, suffer from the general inefficiency of radio transmission due to the lossy air channel and a vicinity to the water-rich tissue, particularly in wireless body area networks (WBAN) [6, 31, 37]. Originated in activity recognition, there exist methods to align measurements offline, after the recording [1, 5, 8, 9, 50]. The used gestures and motion patterns are, however, not incidental but rather tend to be cumbersome, obtrusive, and suffer from inaccuracies due to soft tissue deformation and delays due to motion sequences and inertia of the body parts [30, 53].

In recent years, a novel yet promising approach emerged which utilizes the limited volume of the human body as a transmission medium: intra-body communication (IBC). The technique is somewhat located between wired and wireless communication. Since its proposal in 1995 [56], many researchers aimed at optimal signal couplers and modulation techniques, and developed diverse transceiver circuits ranging from the prototypical PCB [18, 36, 52] to the chip-casted high-level ASIC [14, 15, 45]. Outside the laboratory environment, these trials tend, however, to show less reliability, e.g. due to grounding issues [19]. Except for the discontinued attempt BodyCom around 2011 [42], these approaches are usually closed-source and not yet commercially available. Hence, academic research still focuses on the development of transceivers – advances in reliability, energy efficiency, and data throughput – while the benefiting applications have not been explored yet. One of the most important but, to our knowledge, not yet investigated possible applications of IBC is the synchronization of independent wearable devices in distributed, body-worn sensing systems.

In this paper, we propose the use of off-the-shelf wearables' integrated single-lead ECG sensors for the detection of artificial synchronization signals, induced into and propagated throughout the human body as the limited and hence more efficient transmission channel. We investigate a suitable modulation scheme and evaluate the precise detection of these landmarks. We further demonstrate the method's general feasibility on the example of the implicit synchronization of two wrist-worn devices solely by the wearer approaching a desktop, illustrated in Figure 1. Our research does not intend to compete with cutting-edge research in IBC regarding efficiency and data rate. Instead we aim for the use of accessible and commercially available devices to pave the way for applications which can directly be translated to future single-chip solutions, specifically designed for IBC, when finally made available.

2 RELATED WORK

In the following, the state of the art in ECG and synchronization techniques for wearable devices as well as the relevant research in WBAN and IBC are briefly summarized.

2.1 Wearable Electrocardiography

In clinical settings, electrocardiography (ECG) is the *gold standard* to monitor the heart activity and to diagnose heart diseases. Each contraction of the myocardal muscle is initiated through action potentials which polarize the heart. The accumulated electric field spreads in tissue and is eventually detectable at the skin surface. To derive the typical ECG waveform with its prominent QRS complex, traditional lead systems apply up to 12 wired, wet gel electrodes to capture the electric potential differences across the limbs or torso [2, 17, 22]. Advances in miniaturization enable more convenient and efficient mobile devices [55]. The setup of conventional ECG remains, however, too uncomfortable for the continuous long-term monitoring in ambulatory settings. The first wearable ECG devices were chest straps which dry electrodes resembled lead I across the heart [25]. In the last decade, these devices were successively replaced by more convenient, wrist-worn devices which primarily apply the optical photoplethysmography (PPG) since it is cheap and easy to implement, but their accuracy still did not catch up with ECG [11]. As a special feature, wrist-worn devices gradually offer a supplementary single-lead ECG sensor for the medical-grade monitoring of heart activity [24]. The user has, however, to touch an electrode with a finger from the opposite arm to again form lead I [3], with potentials from either side of the heart [7]. In general, the use of dry electrodes [13] inevitably results in a very weak signal, ranging from tens to hundreds of μV [10, 20]. Hence, the differential amplifier requires a high input impedance to not load the signal. To improve the common-mode rejection ratio (CMRR), usually an active drive electrode, termed as body bias or driven right leg (DRL) circuit, is used to suppress common-mode interference [46, 51].

2.2 Synchronization Techniques

In both wired and wireless distributed systems, the autonomous devices usually apply protocols such as the popular network time protocol (NTP) [35] and the precision time protocol (PTP) [28] to obtain a precise universal time base. In contrast, wearable distributed systems are often synchronized locally, relative to each other, since absolute time is normally not essential. The available techniques can be grouped into two classes: online and offline. The online synchronization of devices at runtime requires the continuous coordination and tuning of the local clocks. The methods primarily rely on wireless communication since wired links, to share a master clock, are uncomfortable and obtrusive. Because of the limited resources on board, the methods for wireless sensor networks (WSN) [27, 47] primarily focus on energy efficiency [55]. Nevertheless, also the mostly applied Bluetooth [41, 43, 44] suffers largely from shadowing effects due to the devices' direct attachment to the water-rich human body [6, 31, 37]. Offline synchronization methods, in contrast, use external incidents to align the signal channels afterwards, in a post-processing step. Originated in activity recognition, Bannach et al. [5] established the concept of aligning time series through the correlation of specific motion patterns such as clapping, shaking, or jumping. In recent years, more advanced methods using motion patterns [8, 9, 30, 50] or cough events [1] have been proposed. Even the white noise inherently present in physiological signals was proposed for the correlation and alignment of signal channels [49]. The "naturally synchronized" heartbeat has also been used in a time division multiple access (TDMA) protocol for medium-access control (MAC) [29]. In our previous research on *PulSync*, the heart rate variability (HRV) serves as a unique fingerprint to align sensor recordings from different wearable devices [53].

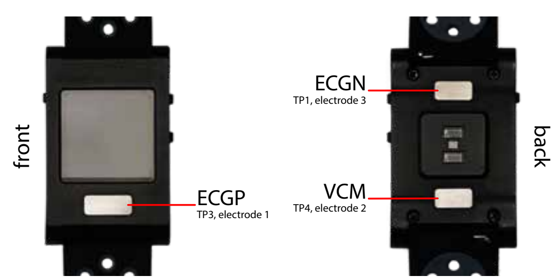

Figure 2: *MAXREFDES101#* [33] ECG sensing device with three electrodes: positive input (ECGP) at the front, negative input (ECGN) and body bias (VCM) at the back.

2.3 Intra-body Communication

In 1995, Zimmerman [56] introduced an innovative alternative to the popular radio: intra-body communication (IBC). It is also referred to as body-coupled communication (BCC) and, since 2012, included in the IEEE 802.15.6 standard for wireless body area networks (WBAN), designated as human body communication (HBC) [23]. The promising technique uses the human body as an alternative transmission medium to transmit information across a user's skin. In contrast to the busy air channel, the body is free, its limited distribution volume improves the energy efficiency, and, outside the body, the abruptly decaying near-field is less susceptible to eavesdropping [16, 26]. Hence, IBC can be seen as an intermediate principle between wired and wireless communication, with advantages over both. As surveyed in [38], two primary techniques are distinguished: the original capacitive coupling (CC) and galvanic coupling (GC). Since the electrode setup is inherently given by the wearable devices used in this work, only the relevant CC is detailed. Two stacked electrodes are used of which one faces the skin and couples to the body while the other one provides a delicate return path through the environment. By varying the electrodes' potential difference, the transmitter modulates the quasi-electrostatic field of the body. The induced current flow among the electrodes at the receiver again results in a tiny but detectable potential difference. The slight displacement current in the order of pA can be assumed to pose no health risk. The body channel's high-pass characteristic is most suitable for the frequency band 100 kHz to 50 MHz, limited through partial resonance of the human body [12, 26, 34]. Diverse models have been derived to understand and simulate the effect of the tissue composition on the transmission characteristics and transfer function [4]. Also the electrodes' size and distance are influencing these parameters [34]. The primary issue of CC is, however, the weak return path through the environmental ground that is sensitive to changes [12, 19, 56]. For floating devices, which do not share a common potential, the signal quality and amplitude decrease significantly by about −60 dB [21]. Stationary transmitters with a link to common ground, consequently achieve a much better signal-to-noise ratio (SNR) and the devices' direct capacitive coupling allows to keep circuits less complex [19, 36, 52].

3 SYNCHRONIZATION METHOD

We present *IBSync*, a novel method that uses the human body as a unidirectional communication channel to provide landmarks and temporal information to body-attached devices. Similar to CC in IBC, a transmitter can either be attached to the subject or hidden and embedded into an object such as a desktop, representatively examined in this work (Figure 1). In this way, either the intentional and continuous, or even the implicit and incidental synchronization are possible by means of the obtained landmarks. Since a uniform pulse train is not unique but confusable, additional information can be appended which contain e.g. an incrementing packet counter, a random value for unique landmark patterns, or even context information. The modulated quasi-electrostatic field changes virtually instantaneously and is detectable throughout the entire body surface. In both offline and online applications, *IBSync* therefore enables the precise alignment of measurements or even the exact temporal allocation of landmarks in absolute time.

4 SYSTEM DESIGN & EVALUATION

Since there exist no commercially available IBC transceiver modules, we propose the use of the emerging single-lead ECG sensors provided in recent wearable devices. Their AFEs are carefully designed with regard to energy efficiency and the sensitive detection of tiny potential differences. Thus, they offer themselves to be repurposed for the detection of the proposed synchronization signals.

4.0.1 Stationary Transmitter. The setup of the transmitter is kept simple and consists of an *MSP430FR5969* [48] microcontroller and a single electrode, made from metal foil, that is directly connected to a general purpose output pin. The electrode has a size of $16 \times 32\,\text{cm}^2$. As illustrated in Figure 1, it is fixed under the front edge of a desktop and couples to the subject's arms through a 1.5 cm plate of wood and plastic. Supplied by and grounded through a USB link to a computer, connected to mains, the microcontroller is regularly, every 2.5 s, instructed to send a synchronization signal. The pulses are generated by switching between 0 and 3.3 V at tuned 20.0 Hz.

4.0.2 Wearable Receiver. Two off-the-shelf *MAXREFDES101#* [33] wrist-worn devices are utilized since they grant access to configuration, source code, and raw measurements. The embedded ECG AFE *MAX30001* [32] provides both very high input impedance $> 1\,\text{G}\Omega$ and CMRR > 100 dB. In this way, it enables the unloaded detection of the displacement current's tiny voltage drop between the electrodes. The measurements are sampled at 128.0 Hz and directly recorded to the internal flash memory. As depicted in Figure 2, the devices have three electrodes: The positive input (ECGP) at the front is kept floating and hence couples to the environment. The negative input (ECGN) couples to the body and enables the measurement of the potential difference in reference to ECGP. The third electrode (VCM) serves as a body bias and DRL circuit to improve the CMRR. Its activation connects the body through a $200\,\text{k}\Omega$ resistor to the device's internal common-mode voltage $V_{CM} = 0.650$ V.

4.0.3 Signal Modulation. As illustrated in Figure 3, the transmitter capacitively modulates the body's quasi-electrostatic field with a rectangular wave and, hence, induces tiny displacement currents which appear to the receiver as the signal's derivative, the charging and discharging current peaks respectively [52, 54]. Although not ideal in terms of bandwidth and efficiency, the generation of square waves in an on-off-keying (OOK) modulation scheme is simple and hence reasonable. A landmark packet consists of 8 pulses as a preamble, one gap and one pulse as delimiter, 8 pulses or gaps to represent the 8 bit of transferred data, again one pulse and one gap as delimiter, and finally 4 pulses as a terminator.

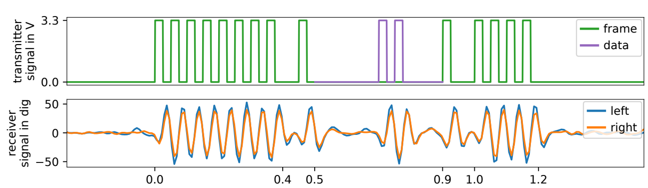

Figure 3: Landmark packet of TX (top): 8 pulses preamble, gap and pulse, 8 pulses or gaps data in OOK scheme (violet), pulse and gap, and 4 pulses terminator. Matched RX landmark signals (bottom): left (blue) and right wrist (orange).

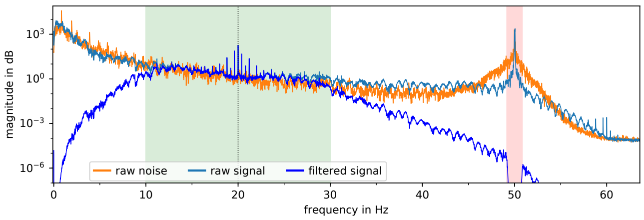

Figure 4: Environmental noise floor (orange), spectrum of the raw (light blue) and the filtered signal (dark blue) to be matched. Notch (red) and band-pass (green) filter.

4.0.4 Signal Demodulation. As shown in Figure 4, the floating sensors catch a broad noise floor from the environment. Therefore, we propose the use of zero-phase forward-backward filters to extract the weak synchronization signal. First, an anti-aliasing 4th order (2×2^{nd}) low-pass filter with a cutoff frequency of 63.0 Hz $< f_s/2$ is applied. The mains' peak at 50.0 Hz is then suppressed using a 12th order (2×6^{th}) notch filter. Finally, the required frequency band, i.e. from 10.0 to 30.0 Hz, is extracted with a 4th order (2×2^{nd}) band-pass filter. As discussed subsequently, the bandwidth is required to cover the sidebands, the modulation's harmonics, which allow for a faster transient response. As illustrated in Figure 5, the short-time Fourier transform (STFT) is applied (top) to detect the landmark frame (Figure 3) within the noisy measurements. Intervals which contain the associated frequency component, i.e. 20.0 Hz, identified by means of the determined signal-to-noise ratio (SNR, middle), are then further inspected using the Pearson product-moment correlation (PPMC) coefficient r [40] (bottom). For each interval, the positions with maximum and significant correlation between a template, derived from the packet frame, and the captured signal unveils the potential landmark positions to be matched. To finally assign the coincident landmarks, those are either correlated considering the unique data segment between the delimiters, or matched by means of their contained binary information. The data are decoded according to the OOK scheme, by means of a simple amplitude interpretation which distinguishes the low 0 and high 1 pulse periods.

4.0.5 Results & Discussion. Before the performance evaluation of the proposed *IBSync* method, the suitable carrier frequency and required bandwidth for the utilized ECG AFE have been determined. To estimate the sensors' noise floor (Figure 4) we recorded 60.0 min of measurements in a usual living space while sitting, working at a computer, walking, and doing different gymnastics. Accordingly, the frequency band from about 10.0 to 48.0 Hz would be applicable. While the body channels' high-pass characteristic favors a higher carrier frequency, the sampling rate of 128.0 Hz, and hence a Nyquist frequency of 64.0 Hz, demands for a lower one to increase the sample coverage per unit pulse period. As a trade-off, the decision was made on the carrier frequency of 20.0 Hz. The bandwidth has been chosen to cover the required harmonics of the sidebands to adequately reconstruct the landmark and to allow for a fast transient response. To evaluate *IBSync*'s performance and to demonstrate its general feasibility, 15 min recordings from three settings have been conducted: directly touching the transmitter electrode achieved an alignment accuracy of 0.113 ± 2.627 samples (0.886 ± 20.526 ms) with $\bar{r}$ = 0.973 ± 0.015, touching the desktop surface above the electrode with both hands 0.371 ± 5.107 samples (2.901 ± 39.901 ms) with $\bar{r}$ = 0.910 ± 0.063, and sitting at the desktop without touching the electrode 0.203 ± 1.633 samples (1.587 ± 12.755 ms) with $\bar{r}$ = 0.956 ± 0.022. Due to the slow carrier frequency, a landmark data packet with in total 24 pulse periods takes 1.2 s. Consequently, the data throughput is apparently not sufficient for the transmission of larger data. The correlation of landmarks with unique data segment increases, however, specificity and accuracy, and furthermore enables their temporal allocation. Since the transmitter's separation from common ground would considerably decrease the signal amplitude, the system is not entirely wearable yet. Improvements of the transmitter's electrode setup and modulation would likely solve this issue. While the heart's QRS complex is almost invisible without touching the front electrode, the artificial landmark signal would superimpose and interfere with the natural ECG if lead I is formed and the transmitter is within reach.

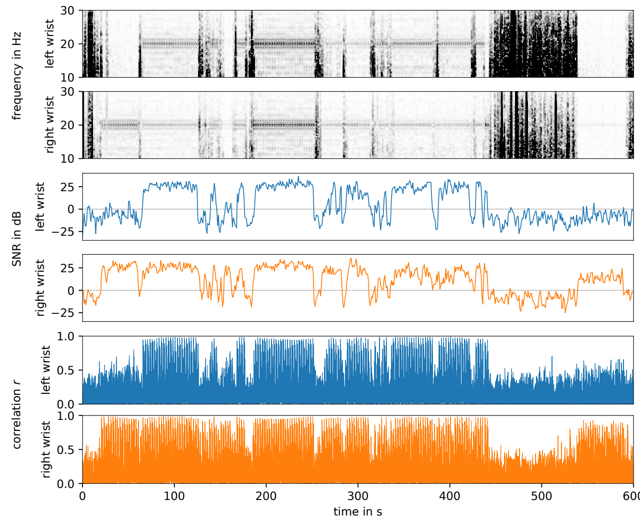

Figure 5: Excerpt from in-the-wild recordings: short-time Fourier transform (STFT) with a window length of 3.6 s and 50 % overlap (top); signal-to-noise ratio (SNR, middle); Pearson's r, normalized cross-correlation (bottom).

5 CONCLUSION

With *IBSync* we presented a novel method for the precise synchronization of independent wearable devices. The provided landmarks can be used for the intentional or implicit and incidental synchronization, in both online or offline applications. We further presented an exemplary system using commercially available wearable devices with ECG sensors as receiver nodes and a simple custom transmitter embedded into a desktop. The achieved synchronization accuracy apparently depends on the coupling strength and signal quality. In three scenarios, we achieved a promising accuracy of 0.886 ± 20.526 ms touching the electrode, 2.901 ± 39.901 ms touching the desktop, and somewhat unexpectedly good 1.587 ± 12.755 ms leaning back in the chair and coupling with the thighs. The receivers' low sampling rate of 128.0 Hz limits, however, not only the achievable accuracy but also the realizable carrier frequency to 20.0 Hz. Nevertheless, we did not only show the general feasibility of *IBSync* but also outperformed the popular motion-based offline techniques with a typical accuracy in the order of 46–250 ms [1, 50].

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