

Ving: Bootstrapping the Desktop Area Network with a Vibratory Ping

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ABSTRACT

The emergence of the Internet of Things will cause the density of wirelessly networked devices to increase significantly. As the industry and density continue to grow, enabling and managing networks of these devices in a scalable manner without constant user interaction becomes essential. Noting that information about physical context can guide interactions between devices, we introduce the *desktop area network* and Ving, a vibratory ping architecture that enables it. Ving is based on the wireless vibratory communications channel between a vibratory motor on one device and an accelerometer on another. Because vibratory communications is a physically-coupled, surface-constrained communications domain, Ving allows devices to bootstrap networks within their physical context, creating a literal desktop area network. Such context establishment and network creation enables a new class of applications for smartphones and embedded devices. We present several of these applications, discuss our preliminary implementation of Ving, compare Ving to alternate methods of context establishment, and suggest potential research challenges stemming from the widespread use of Ving.

Categories and Subject Descriptors

C.3 [COMPUTER-COMMUNICATION NETWORKS]: Network Architecture and Design

Keywords

Vibratory communications; Contextual networking; Desktop area network; Device discovery

1. INTRODUCTION

The Internet of Things (IoT) will bring billions of new, low-power, networked hosts online within the next decade [3]. As homes, offices, restaurants, and other public spaces fill with these service-providing devices, there is a growing need for other devices—especially those that are mobile and user-facing—to discover and associate selectively with the subset of devices that are relevant to their users. Ide-

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ally these associations would be formed with both context-awareness and low user burden.

Imagine a scenario in which a group of students are meeting to practice for a presentation in a library. They want to share screens between their tablets, so they scan for available devices. In a modern library the students might be overwhelmed by the number of available devices. They might see thermostats, smart bulbs, fitness trackers, wireless locks, and a variety of other devices also advertising connections. While the goal of connecting to the devices at their table is simple with an understanding of context, it is muddled by the cumbersome process of sorting through the list of available devices and manually pairing with the correct ones. Current networking capabilities are not able to use the shared desktop context to establish the connections transparently.

To solve this problem, we propose Ving—a vibratory ping architecture—that allows devices to discover other devices on a shared desktop and bootstrap higher bandwidth communication channels, such as Bluetooth, based on this discovery. Ving-enabled devices transmit a discovery Ving when their accelerometer senses that they have been placed on a flat surface. Devices that receive this Ving may then respond by attempting to connect with the transmitting device. As more Ving-enabled devices are added to the surface, they are added to the desktop area network. This association makes connection establishment less burdensome for users by allowing devices to transparently create and use their own shared context.

As prior work has established [14] and our own implementation corroborates, unobtrusive vibratory communication of satisfactory bit rates can be achieved by using the vibratory motors and accelerometers already present in many mobile and wearable devices. Moreover, accelerometers and vibratory motors are already present in some larger devices such as laptops.

Still, further research on Ving's security, viability, and usability is required before widespread adoption of the idea could be conceivable. Exploring these open questions will not only lead to a better understanding of the intricacies of vibratory communications and the Ving architecture, but they will also give insight into the wider challenges of context-aware connection formation.

2. RELATED WORK

Prior work demonstrates successful vibratory communications; however the applications that are proposed in prior work do not take advantage of the limited physical propagation properties of vibratory communications to establish a shared desktop context, nor do they explore the applications made possible by this context. Related work does propose applications that both actively and passively use vibratory signatures for security and bootstrapping higher bandwidth communications, which we discuss below.

Vibratory communications. Several prior works demonstrate vibratory communications [6, 14, 18]. While earlier works demonstrate 1 bps [6] and 4 bps [18] communication rates respectively, more recent work achieves 200 bps using custom hardware and 20-80 bps on unmodified smartphones [14]. These contributions show that vibratory communication is possible at reasonable bit rates to implement the Ving architecture, as our own implementation corroborates; however, they do not present potential application spaces for vibratory communication, which is the focus of this work.

Security applications. Most of the previously proposed applications of vibratory communication utilize the claimed privacy of a shared vibratory signature to establish trust. This vibratory signature can be passively obtained by bumping or shaking a pair of devices together [11, 15], or actively transmitted by a vibratory motor [6, 15]. One work questions the inherent privacy of vibratory communication due to acoustic leakage, and improves on privacy with intentional acoustic interference [14]. However, they do not explore specific applications for vibratory communication. It should be noted that our work makes no claims about the security or privacy of vibratory communication.

Bootstrapping. Related work also proposes the use of vibration to facilitate higher bandwidth connections. Some of these connections are facilitated by shared passive vibratory signatures, such as those received by multiple wearable devices on the same person [8], or shaking a pair of devices simultaneously [5]. One work proposes bootstrapping connections using vibratory motors to transmit identifying information [18]; however, it requires users to touch custom hardware on the two devices that are being paired, and does not explore the possibilities of bootstrapping unmodified devices without custom hardware, using vibration to establish a shared desktop context, or the possible applications that arise from this context.

3. COMMUNICATION CONTEXTS

Many devices exist that provide services intended for a specific spatial context. For example, imagine a modern cafe. The cafe’s wireless coupon service can use the long-range, building-level context RF communication to communicate with people walking across the street; the ability to control the cafe’s wireless Jukebox can be provided only to customers within the cafe using the room-level context of visible light communications (VLC) [17], which is limited by opaque physical barriers.

When the customer sits down at a table to order a drink, however, neither RF nor VLC are physically suited to discover the cafe’s table-specific ordering service. A basic RF or VLC setup would require the user to search through a list of devices for their table’s ID and manually connect. This problem can be solved by introducing a third level of context—the desktop area network—and the communication channel physically suited to create it—vibratory communication. This new level of context is compared with RF and VLC in Figure 1. When a phone is set on a table, Ving transmits a vibratory ping. This vibration is inherently limited to the desktop area, ensuring the user connects to their own table in a simple and transparent way. An embedded device on the table can detect this ping and bootstrap an RF connection to that phone. Then, through the higher-bandwidth connection, an order can be placed.

In the progression of wireless technology from RF to VLC, Ving, with its ability establish the desktop area network, offers a new method for creating contextually-aware wireless environments, allowing devices to provide users with more relevant and useful services.

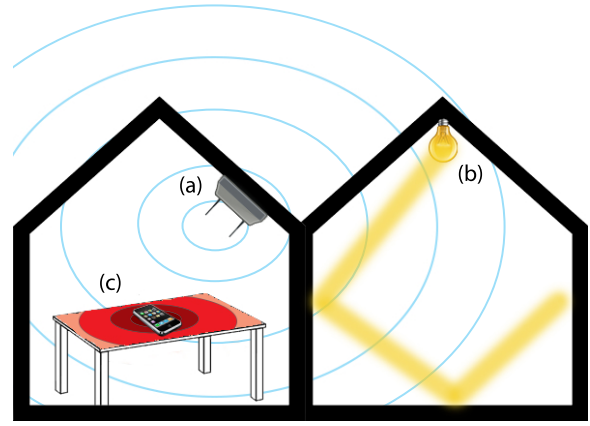


Figure 1: Three communication contexts: a) RF communication which is not limited by physical barriers and is suitable for building level services, b) VLC which is limited by opaque physical barriers and is suitable for room level services, and c) Vibratory communication which is limited to a solid surface and suitable for desktop constrained services. Developing vibratory communication and the Ving architecture enables new connection patterns and offers a potential next step in advancing context aware wireless technology.

3.1 Motivating Applications.

We have identified four distinct connection patterns enabled by the desktop area network, which are portrayed in Figure 2. We present these connection patterns in order of increasing suitability for the Ving architecture, motivate each with an application, and discuss whether they could be achieved by alternate technologies such as range-limited RF communication.

First-time connection initiation. Upon setting up many IoT devices for the first time, a user must pair their smartphone with the device using an RF communication protocol. This pairing process is often manual, forcing the user to select the device from a list of available devices and possibly enter a pairing key. The process can be more complicated if there are multiple instances of a single type of device within RF range. Ving provides a simple way of initiating this new connection, even if there are multiple instances of the same device nearby.

For example, if a family buys five fitness trackers and needs to set up individual connections with the devices, the family’s smartphones may attempt to connect with the wrong device. If the fitness tracker was Ving enabled, simply setting a smartphone on the same surface as one of the fitness trackers would initiate the correct connection.

Range-limited RF protocols such as NFC or RSSI thresholding for proximity could support this first connection pattern. A range-limited protocol would require the user to place their smartphone near the device with which they wish to connect, which should not be a problem for the setup of a new and clearly visible device.

Context awareness for existing connections. Devices that a single user owns and trusts can provide wireless services to other devices through established and persistent RF connections. These connections likely do not need to be repeatedly bootstrapped because their RF visibility alone provides enough contextual relevance to warrant forming a connection. They still may benefit from more precise contextual awareness, and Ving can provide desktop area contextual awareness—essentially desktop presence detection.

In an application of this connection pattern, a user’s personal laptop and smartphone maintain a Bluetooth connection whenever

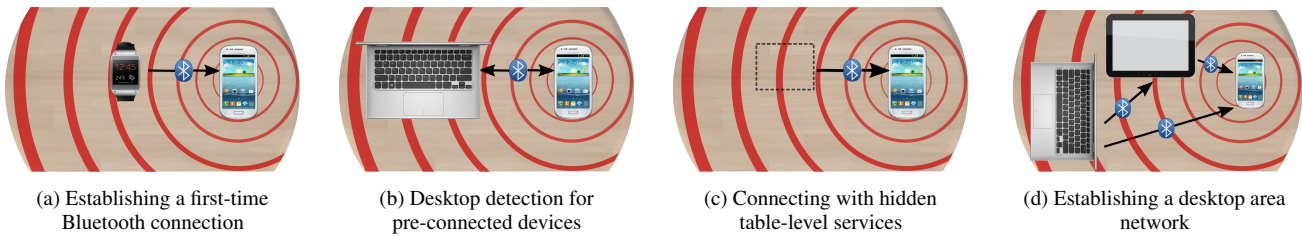


Figure 2: Applications of Ving. a) A Ving (originating from the phone) facilitates establishment of a first time Bluetooth connection with a new device. b) Devices in a pre-established Bluetooth connection use Ving to discover shared desktop context. c) A device uses Ving to connect to a hidden device providing a table-level service over Bluetooth. d) A device uses Ving to connect to multiple devices and form a desktop area network over Bluetooth. These applications show the connection patterns that are enabled by Ving.

possible. The user would like the smartphone to provide notification forwarding when it is placed on the desk next to their laptop. Ving can enable this application by allowing the laptop to sense its shared desktop context with the smartphone and initiate the notification forwarding service over the already established Bluetooth connection.

While range-limited RF communication protocols or RSSI thresholding could enable this connection pattern when the devices are within close proximity, proximity here is not a good marker of shared context. This will cause intermittent or unintended service initiation. Ving provides a natural yet deliberate action that establishes shared desktop context.

Effortless desktop connection initiation. IoT devices in public spaces often have services that they wish to offer within that space. Some of these services may be provided at room level, but others may be provided with desktop granularity. Ving allows devices to establish connections with devices providing services for the specific desktop that they occupy.

For example, a restaurant would install Bluetooth devices at each table to allow the customers occupying that table to order, request service, and pay their bill. A customer sits down and places their phone on the table in front of them. This effortless motion initiates a Ving, which then bootstraps a wireless connection with the table that the customer is occupying.

This application would be difficult to achieve with range-limited RF protocols or RSSI thresholding. A Bluetooth connection associated with a specific table would certainly be visible at nearby tables, and customers at nearby tables may even be closer to the Bluetooth transmitter than a customer sitting at the far end of the transmitting table. An extremely short range RF protocol such as NFC would require each customer to tap a specific spot on the table or installing an NFC device at each seat, neither of which scales well for multiple users at the same table. Because Ving exploits the table context naturally, it may be more suited to provide table-bound services.

Effortless desktop network initiation. There are situations in which users may wish to use the desktop context to initiate their own network of multiple devices in which the participants are clearly defined and limited by the desktop. If a number of devices are placed on a table, and one device wishes to share data over a wireless connection to all devices on the table, but only those devices, Ving could be used to bootstrap the connection, ensuring the sharing network operates only within the desktop context.

For example, a group of students may be studying at a library and wish to share files with the rest of the group at the table. As devices are placed on the table they can advertise a file sharing service on the local network through a Ving. The receiving devices would monitor this service and alert the new device of their own file

sharing services, establishing a desktop area network, and allowing the users to share files with only the devices at their table.

Establishing this mobile, ad-hoc, desktop area network of devices would be difficult with RF communication protocols, and users would either be forced to search through a list of available devices or services or individually connect to the devices at their desktop in another manner.

4. ARCHITECTURE

The Ving architecture enables devices to transmit a vibratory ping when placed on a table or other flat surface. The information encoded within the vibratory ping, described in detail below, can be used by the receiving device to bootstrap a higher bandwidth connection with the transmitter. Ving is designed to enable communication over higher bandwidth channels because sustained vibratory communication would be slow, annoying, and relatively high power. A single Ving, on the other hand, would be short, unobtrusive, and still enable applications that depend on a shared desktop context. The steps below describe a single Ving interaction.

1) Detect desktop context. Ving enabled devices use their accelerometer to detect when they are placed on a desktop.

2) Advertise connections and services. After detecting the desktop context, a Ving enabled device begins or continues its availability on the appropriate communication channels. The exact nature of this availability is communication channel dependent. For example, Bluetooth classic enabled devices would become discoverable, Bluetooth Low Energy devices would begin or continue advertising, and WiFi connected devices would ensure publication of a Zero-Configuration networking service.

3) Transmit a Ving. The device transmits a Ving. The Ving contains information indicating available communication channels and the device's address. The format of the address is motivated by data rate. If the Ving enabled device can transmit a Ving at 20 bps, then a 1 second Ving could contain up to four bits indicating the available communication channels and a 16 bit address. If the Ving enabled device can transmit at the 200 bps achieved by custom hardware in prior work [14], a Ving shorter than 1 second could contain information on available communication channels along with a full length, 32-128 bit address, a range allowing for IPv4, IPv6, and Bluetooth addresses. A Ving lasting 0.1 seconds could contain up to four bits indicating available communication channels and a 16 bit address. A shorter Ving is quieter and lower power, but full length addresses would be simpler to integrate into existing communication protocols.

4) Receive the Ving. Other Ving enabled devices sharing a desktop with the transmitting device receive and decode the Ving.

5) **Scan for advertisements.** The receiving device(s) scan the communication channels indicated by the Ving to discover the transmitting device's services and identity.

6) **Use available services.** The receiving device(s) could then initiate a connection with the transmitting device, use the transmitting device's services, or use knowledge that a known device is sharing the desktop context to enable specific features.

5. PRELIMINARY EVALUATION

As we state in Section 2, prior work achieves vibratory communication on unmodified smartphones and custom hardware. To further verify the feasibility of the Ving architecture, we implement a custom vibratory communications system and perform a preliminary evaluation of the system.

5.1 Proof-of-Concept Implementation

To explore the viability of Ving, we implement custom hardware that incorporates the necessary sensors and actuators needed to test vibratory communications as shown in Figure 3. This hardware uses a Precision Microdrives C10-100 LRA vibratory motor [13], a Texas Instruments DRV2603 haptic motor controller [16], and an InvenSense MPU-6500 digital accelerometer [7]. These components are either used in, or similar to those used in modern smartphones. We achieve a communications bit rate of 20 bps, which corroborates with what prior work achieves under similar conditions [14]. Design files and software for our implementation are available online.¹

5.2 Preliminary Results

We perform a preliminary evaluation of Ving to verify feasibility. This evaluation consists of verifying that the sound of sending a Ving and the energy cost of sending and receiving a Ving are reasonable. Prior work establishes that the sound of vibratory communication is acceptable in normal sound level situations by comparing the sound of vibratory transmissions on different materials to ambient noises recorded in common locations [14]. The sound of vibration would be even less of an issue if vibratory communication rates on unmodified smartphones increase to the 200 bps that prior work achieves on custom hardware [14], as this would allow a Ving to be as short as 0.1 seconds.

To evaluate the energy cost of transmitting, we measure the current draw of a vibratory motor to be about 70 mA at maximum amplitude. The data dependent current draw of the On-Off-Keying that we implemented would make the average current draw of transmitting a Ving 35 mA. While this is relatively high when compared to low power RF communication protocols such as Bluetooth, it is comparable to an active WiFi connection [1]. Moreover Ving is used for establishing context rather than continuous communication. This reasonable current draw combined with the short duration of a Ving, which consumes on the order of tens of mJ per Ving, falls well within the energy budget of a smartphone.

To evaluate the energy cost of receiving, we measure the current draw of the InvenSense MPU-6500 commonly found in smartphones sampling at 4 kHz to be about 450 μ A [7]. Many accelerometer applications, such as step counting and wake-on-tap, perform constant processing of accelerometer data at relatively low power, and Android even requires that constantly on accelerometer applications draw less than 500 μ A [4], allowing us to conclude that constant listening for Ving would be well within a smartphone's energy budget. Further optimizations such as listening only when on a flat surface and utilizing an accelerometer's wake-on-motion interrupt to start processing could be utilized to lower the receive power of Ving.

¹<http://www.github.com/lab11/ving>

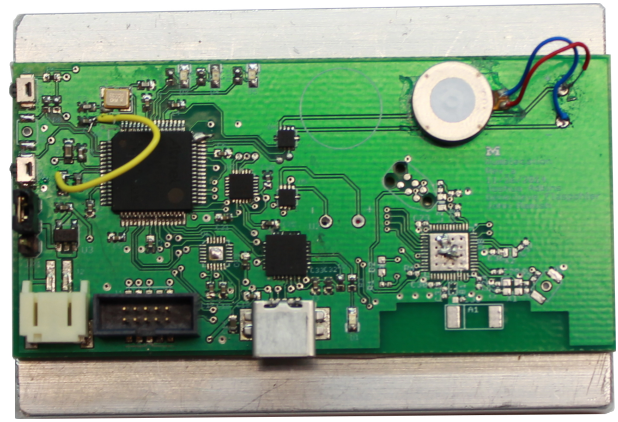


Figure 3: Custom, smartphone emulating, hardware used to evaluate vibratory communication. This shows that physically unmodified smartphones could transmit and receive a Ving at 20 bps.

6. DISCUSSION

The proposed Ving architecture uses the restricted communications domain of vibratory pings to enable a desktop area network, hopefully helping to establish relevance and context among a growing number of networked devices. However there are still open questions about the security, viability, and usability of Ving.

Security. Ving allows devices to connect and discover services from previously unknown devices, possibly in a user-transparent manner. Establishing trust with these devices and authenticating their services could be necessary for many applications of Ving, including screen sharing and mobile payments, among others. While this is an open problem, it is not one that only affects the Ving architecture, but rather any architecture that proposes networking with unknown and potentially malicious devices. Ving's proposal of effortless, user transparent connection patterns does have the disadvantage of removing the visual, human check from the connection process. This could be solved by involving a trusted third party in the authentication process.

Ving also requires frequent, high data rate sampling of the accelerometer. Several works show that sampling physical sensors at high data rates can be used as an eavesdropping technique [10, 12]. A secure implementation of Ving would have to consider these limitations, and prevent possibly malicious userspace applications from accessing the accelerometer at high sampling rates, and eavesdropping on potentially sensitive information.

Several attacks could directly take advantage of the Ving architecture. For instance a device could carry out an energy depletion attack by repeatedly transmitting a Ving, causing other devices on the desktop drain their battery while processing these Vings. A malicious device could send interfering vibratory signals and prevent Ving on a desktop. While these attacks would disrupt operation of Ving on a single desktop, they would not pose serious risks to Ving users, and would be easily detectable.

Viability. There are also open questions about the technical viability of Ving. Higher vibratory communication bit rates could be achieved by making simple modifications to smartphone hardware [14], but manufactures would have to be motivated to make this change.

Prior work does explore other technical questions such as bit error rates, reliability on different surfaces, and distance at which reliable vibratory communications could be achieved [14]. This work also shows acceptable results for some of these metrics, however these

questions warrant further experimentation before the Ving architecture could be broadly adopted. Further experimentation could also verify that vibratory communications is viable for all of the devices that we propose, including devices such as watches and laptops that assume a different form factor than our test platform.

Low power vibratory communication receivers would also need to be created. While we discuss in Section 5 that vibratory communication receive power is acceptable, there is plenty of room for improvement. Many applications require continuous low power collection and processing of accelerometer data such as step counting and tap detection, and these technologies could be leveraged to create low power Ving detection hardware and software. Prior work also shows that the creation of near zero-power Ving wake-up hardware may be possible through the coupling of piezoelectric tabs with nano-power comparators [9].

Usability. Several steps would be necessary for the widespread adoption of Ving. First and foremost, a sufficient density of devices with vibratory motors to transmit a Ving and accelerometers to receive a Ving would have to exist. We believe that this density is already sufficient, and will continue to grow. Most user-facing, Ving-transmitting devices such as smartphones, tablets, watches, and even laptops have or will soon have vibratory motors for haptic feedback [2], and many small, low-power sensor nodes have accelerometers that would allow them to receive a Ving. Adoption would also require the creation of a standard that specifies both the detection and resolution of Ving conflicts and the structure of Ving messages.

7. CONCLUSION

The growing number of IoT devices offering wireless services in diverse application spaces makes the issue of simple and user-transparent connectivity a challenging problem. Establishing physically constrained communication contexts allows developers of wireless technologies to shrink the scope of the problem and enable new applications while providing users with more natural connection patterns. Ving allows a user to exploit the desktop area context to tightly limit the bootstrapping of a communication channel, making it a useful next step in the progression of wireless technology. Add to that Ving’s capacity to be implemented on existing smartphones with only minor software changes, and vibratory communications seems well positioned as a new method for establishing context.

8. ACKNOWLEDGMENTS

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