FPGA Rapid Prototyping of NFC-TENS for Smartphone Healthcare

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Abstract—**With the Near Field Communication (NFC) capabilities, emerging smartphones can expand customized hardware in outside. However, the realization of such technology is still in its infancy. This paper proposes a prototyping technology of NFC tag protocol used for transcutaneous electrical nerve stimulation (TENS) converter for smartphones healthcare aids. The NFC-TENS design consists of four layer of ISO/IEC-14443A tag standard with a TENS realized in the application layer. One side of which is the wireless communication to NFC reader of smartphone and the other side the TENS pulse signal generation for massage. The implementation is based-on FPGA rapid prototyping technology combined with the Android system that supported for NFC standards. The results reveal that smartphones healthcare is feasibly improving the healthcare behavior while comparing with the traditional TENS.**

***Keywords*—FPGA rapid prototyping; TENS; NFC tag protocol; smartphone healthcare; Manchester coding; Modified Miller coding; HW/SW co-design**

I. INTRODUCTION

Recently, the popularity of smartphones and the trend of open system brought advanced advantage for new applications. This enabled the interesting of academic and industrial in innovation, research and design of creating high value-added services for cell phones, such as the development of real-time mobile healthcare services [1] is becoming feasible. However, in the practice, the traditional interface expansion has many limitations despite of a variety of communication functions are provided in smartphones. For example, the available USB interface of smartphones generally acts as a device rather than the host, which is not suitable for use as a controller. In recent years, the USB Association launched OTG (On the Go) solution [10] for the requirements of peer-to-peer communication between two smartphones or phone to other devices, but they need connected with an inconvenient wire. Although Bluetooth interface provides wireless communication, there still exists a problem of up to several seconds of pairing time in average [11] . Another disadvantage of Bluetooth standard is the external hardware needs an independent power supply, which will unexpectedly cause the cost increasing. One of the brightest stars of tomorrow for use in smartphone may be the near field communication (NFC) technology since it not only provides the tag power in its nature but is comprehensively supported by the API of Android 2.3.3 or later versions [12] . NFC interface has been ready in more and more kinds of smartphone including the Windows8-Nokia systems which has fully supported NFC interface standard in order to promote e-wallet mobile payment services [13] [14] .

In this paper, the research objectives will be focused-on the FPGA rapid prototyping of NFC enabled transcutaneous electrical nerve stimulation, called the NFC-TENS, for smartphone healthcare aids. With such framework, our goal is to improve the traditional electronic acupuncture massage healthcare to be guided by the smartphone operating, and powered by radio frequency (RF) of smartphones, which advantages not saving the design and maintenance costs, but allowing the operator to manipulate with easier user interface such as the touch technology, as well as gains the availability of web services. The design extends the smartphone applications for pressure aided release by issuing various kinks of high voltage narrow pulse trains to stimulate human's motor nerves. This helps relieving the muscle pains of shoulder, neck, waist and limbs, and can be used to care some specific types of disease such as insomnia and fatness. Sometimes it can be used for the purpose of cosmetology.

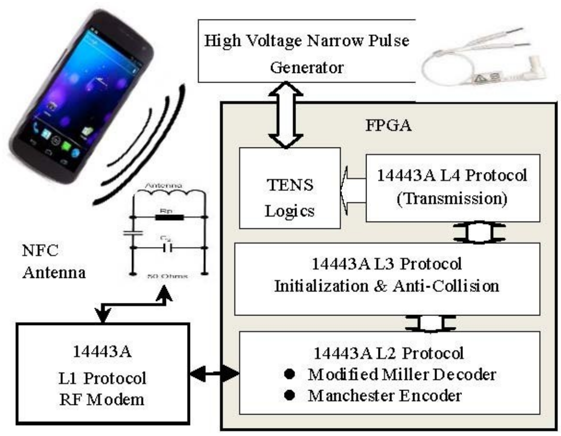


Fig. 1 Architecture of Android mobile healthcare

System architecture is shown in Fig. 1 . In such a system, the NFC smartphones provide a complete mobile operating system and the user-friendly man-machine interface, support the ISO/IEC-14443A NFC standard communication hardware and an API framework. Electronic acupuncture massage health device hardware contains three parts. There are RF

module, NFC tag digital portion and the high voltage pulse converter. The RF module including an antenna and modem circuit which is the layer 1 of 14443A standard. Other three layers of NFC tag are in the digital portion and are implemented by the FPGAs. According to ISO/IEC-14443A NFC tag standard, they are the Modified Miller Decoder and Manchester Encoder in L2, the Initialization & Anti-Collision logic in L3 and applications in L4. The transmission protocol of L4 is realized with the TENS logic which is the electro acupuncture logic for healthcare. L4 is used for communication to the application of smartphone through the NFC API framework. A command-response mechanism can achieve the manipulation of NFC smartphones to electronic acupuncture health entity.

Next, Section 2 describes the related technical principles of NFC smartphone and electronic acupuncture health entity, methods for the realization in Section 3, and the results presented in Section 4, Section 5 a conclusion is given.

II. Related techniques

A. TENS

Electronic Acupuncture Health entity is achieved by way of applying the transcutaneous electrical nerve stimulation (TENS) to import the high-voltage narrow pulse signals to the body to stimulate motor nerves, resulting in muscle groups generate a series of rhythmic but with involuntary contraction of the local movement. Such contraction movement can have a very high predictability of therapy [1]. TENS also provides electrical stimulation analgesic effect, the basic principle is the "gait control theory", which is the use of a weak low-frequency electric current to stimulate the epidermis motor nerve, and then exploit the muscle vibration to achieve the repair effect. Therefore TENS technology has become one of important and legitimate electronic medical aids [2].

Traditional TENS often realized with switching regulator and waveform generator [3] that controlled by a single-chip microcontroller unit (MCU). For instances, the solution of using MCU MSP430F149 as controller and LTC3200-5 H-bridge as high voltage booster which can generate up to 150V stimulate pulses [4], the TENS system design using a PIC 16F84 MCU and two DAC circuits supporting different type of 0~50V square, triangle and sawtooth waveforms [5], etc. These designs are generally cases of software-based implementation that may not be able to achieve system-on-a-chip (SOC) optimization, such as the technical difficulties of multiple electrode expansion. In previous work, we developed a five-parameter command TENS system to simplify the TENS implementation and expansion [15] .

B. Use of near field communication (NFC)

NFC technology evolved from Radio Frequency IDentification (RFID) contactless smart card [6], and its general types including contactless card reader, contactless smart cards such as money Tag and the like, or for the use of information exchange. Their operating functions are integrated on a single chip, the common radio frequency is running at 13.56MHz, and the effective distance is within 10cm. There are several transmission rates to be used, 106kbit/s, 212kbit/s, 424kbit/s [7], and can be up to 848kbit/s in the future.

NFC devices have three operating modes: (1) active mode, to act as a reader, takes the initiative radio frequency (RF) signals to identify and read/write another NFC device; (2) passive mode, can be modeled as a tag to be read/written in a passive response when other reader devices emit radio frequency (RF); (3) bidirectional mode, to create a point to point communication [8], such as smart phones use the NFC Data Exchange Format (NDEF) action protocol to exchange information of name card.

NFC-enabled smartphone devices require a chip with normal NFC protocols controller and security mechanism, and through the software to control the NFC chip settings, status, functions and applications. It can process external Tag access, exchange data with other NFC devices, or even emulate a passive tag to be read by other NFC devices [9].

Android system supports NFC standard since the improved Gingerbread update (version 2.3.3). It can be regarded as the most outstanding technology for the update, including:

1) Adding full API functions for smartphone NFC reader so that Android applications can access almost all the NFC standard tags that existed in current market. It can support standards NEDF records, and protocols such as NFCA, NFCB, NFCF (SONY Felica), NFCV and more.
2) When a NFC tag proximate smartphone within specified range, the program can decide the control over when or what the situation started.
3) Provide limited support for P2P (Peer-to-Peer) transmission for other NFC devices.

Once connection, it is a paired device like Bluetooth [10] that allows smartphone and tag communicate through the command-response mechanism. The biggest advantage of such communication is that the tag does not have to use external power supply. The pairing process is quick and practical. Compared to Bluetooth or Wi-Fi technology, NFC's pairing process can be treated as a very short time.

C. ISO/IEC-14443A NFC standard

ISO/IEC-14443A is one of several kinds of NFC technology standards. Like other standards, NFC protocol is divided into four layers:

1) Layer 1: Physical characteristics
2) Layer 2: Radio frequency power and signal interface
3) Layer 3: Initialization and anti-collision
4) Layer 4: Transmission protocols

A complete specification is existed in every layer, the former three layers are the physical and link layers, and the fourth layer is the data exchange layer which also called the application layer.

Except the RF technology in layer 1, the rest are pure digital technology layers. ISO/IEC-14443A defined RF carrier specification as shown in Figure 2, the upper waveform shows the ASK modulation with 13.56MHz carrier that transmitted from reader to tag. Above the RF, there is the Modified Miller coding signal loaded on it. In the lower waveform, it is the Manchester coding signal loaded on 13.56MHz RF carrier with ASK modulation. In which, the Manchester coding signal is transmitted from tag to the reader [16] .

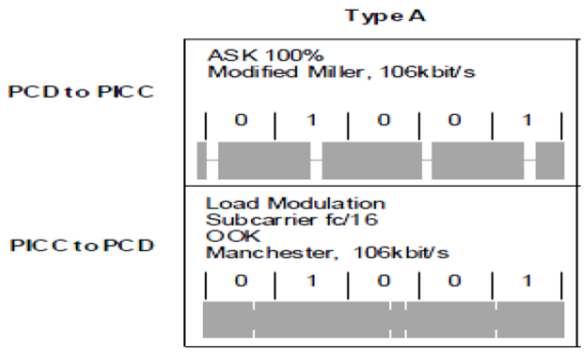


Fig. 2 ASK Modulated waveform for (a) Modified Miller coding, (b) Manchester coding

III. IMPLEMENTATION TECHNOLOGY

In this work, we use hardware and software co-design technology to implement the TENS system. The software part consists of Android application and the NFC API supporting on Android smartphones. The hardware is the FPGA-based rapid prototyping technology for integration and verification of digital part of NFC Tag, i.e., the layer 2 to layer 4 protocols. According to NFC forum, layer 4 is an open layer that allows realizing any type of applications. In which the TENS logic is realized based on our previous work of parameterized TENS system [15] . The use of rapid prototyping technology can gain the advantage of early and quickly finding the problem and achieving the system optimization in the design phase.

A. Pulse modulation stimulator for NFC-TENS

The implementation system includes blocks of man-machine interface (MMI) and NFC protocols, Stimulating pulse train generator and controller in NFC layer 4, high-voltage converter, sense and actuation etc. as shown in Figure 3. The control part generates high-voltage pulses train by the pulse generator and the amplitude modulator, the stimulate section includes a pair of electrode patches and an over current sensing circuit for safety reason.

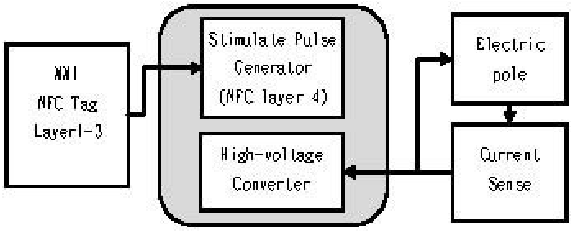


Fig. 3 Block-diagram of NFC-TENS entity

The purpose of electronic acupuncture health entity is to emulate the operation of massage by mainly controlling the voltage and the pulse frequency. The voltage control is used to adjust the stimulate intensity that normally adjusted in about 30 to 150 volts, and the pulse frequency control is for adjusting the stimulate rate. Figure 4 shows a pulse generator model we defined in [15] , in which the inner loop parameters VcMax determine maximum charging voltage, Nc the charging times of the inner loop, Tc is used to calculate the inner loop charge and discharge time, Td the delay time of the outer loop, Np calculate the repeat number of outer loop. The use of combinations of these parameters, one can emulate tapping, kneading and pushing operations by pulse trains. For example a tap function will use without the inner loops, just set VcMax, Td, Np three parameters can be working good, where VcMax determines pulse voltage, Td determines tap intervals, Np is used to determine the repeat numbers of tap.

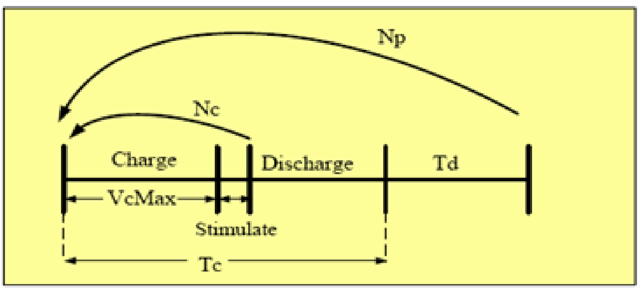


Fig. 4 Timing model of pulse modulator for TENS

The above electronic acupuncture health entity is implemented in FPGA as a NFC-TENS Tag that with ISO/IEC-14443A compliant. In layer 2, the RF power and signal interface layer, the implementation includes clock recovery, Modified Miller decoding with Manchester encoding. Then command-response mechanism in layer 3 to communicate with the NFC smartphone, when the smartphone sends a request (REQA) command to search for tags, Tag required to answer attention request (ATQA) for response, and then responding the universal identification code (UID) to NFC smartphones for the success selection command (SEL). And after anti-collision process being passed, it entering into layer 4, the transmission layer or called the application layer. In this layer the Protocol Control Byte (PCB) command is employed to access our five parameters from smartphone to NFC-TENS Tag. These parameters are directly obtained from the Android operating panel, so that a user can control the TENS by his hands.

B. Applications of Android smartphone for NFC-TENS control on FPGA

In NFC tag accessing process, Android system uses "Intent" to start an activity when a tag is discovered, and activities are registered for the specific technologies on the tag. An NfcAdapter is used to get default adapter in the nfcTENSActivity class. An intent filter is included to receive this intent and specify the desired tech types in a manifest meta-data entry. The action of start NFC activity through Android API is shown as following:

```
private void SetupNFC() {
  Intent intent = new Intent(this,
        getClass()) .addFlags(Intent.FLAG_ACTIVITY_SINGLE_TOP);
  try {
    mAdapter = NfcAdapter.getDefaultAdapter();
    mPendingIntent = PendingIntent.getActivity(this, 0, intent, 0);
    IntentFilter myNfc = new IntentFilter(
                         NfcAdapter.ACTION_TECH_DISCOVERED);
    mFilters = new IntentFilter[] { myNfc, };
    mTechLists = new String[][] { new String[] {NfcA.class.getName()}};
  } catch (Exception e) {
    e.printStackTrace();
  }
}
```

In application layer, smartphone can access the NFC-TENS Tag via get(), connect (), transceive () and close () functions. The {VcMax, Nc, Tc, Td, Np} parameters are packed into a PCB command and transferred to control the behavior of electrical stimulation circuit in FPGA TENS side.

IV. Experimental Results

Combined with technologies of graphical user interface (GUI), smartphone provides a user-friendly interface to replace the traditional simple display and keys. This is the reason why we use smartphone to connect TENS. Therefore the smartphone application for NFC-TENS is developed. A user-friendly Android GUI is presented in Fig. 5.

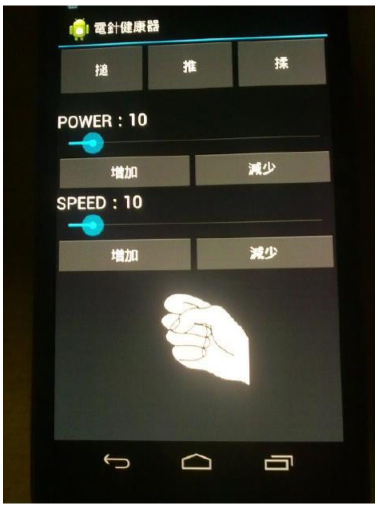


Fig. 5 Smartphone GUI for NFC-TENS

The EP4CE22F17C6 of Cyclone IV E series FPGA is used to implement the digital logic of NFC-TENS, the resource is totally spent 1016 logic elements (LE), which containing 910 combinational logic functions and 496 registers, as shown in Table 1, and the internal circuit block shown in Figure 6.

TABLE 1. FPGA RESOURCE USAGE

Cyclone IV E: EP4CE22F17C6	Used LE
Total logic elements	1,016
Total combinational functions	910
Dedicated logic registers	496

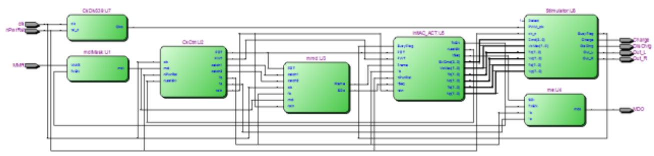
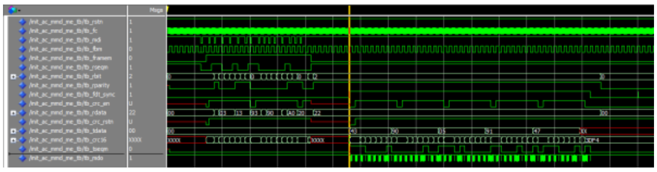


Fig. 6 FPGA internal circuit blocks

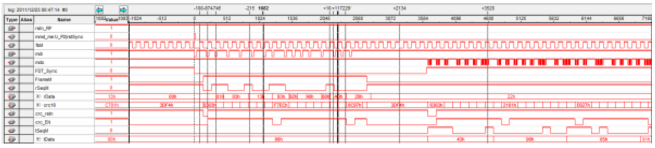
In the work, though the used logic elements are not as large as other applications, but it is so difficult to design and verify such an communication protocol of ISO/IEC-1443A compliant, as well as the TENS logic. The most challenge is the timing verification task. We implement ten more command-response pairs as bellow:

1) REQA-ATQA,
2) WUPA-ATQA,
3) SEL_NVB-UID,
4) SEL-SAK,
5) HLTA-NAK,
6) RATS-ATS,
7) PPSS-PPSS,
8) PCB_I-PCB_I,
9) PCB_R-PCB_R,
10) DeSEL-DeSEL

The verification process is first use ModelSim simulator, but it will not be very reliable because of there are not correct test patterns be obtained. So that we advanced use Altera's SignalTap-II to get a real-time smartphone commands and FPGA response. For example, the SEL_NVB-UID command-response includes the Modified Miller decoding, the command interprets, the response and Manchester encoding. It is presented in Fig. 7 . Where figure (a) is the ModelSim waveform while the figure (b) the SignalTap-II result. From such a comparison, we can confirm the design is correct.



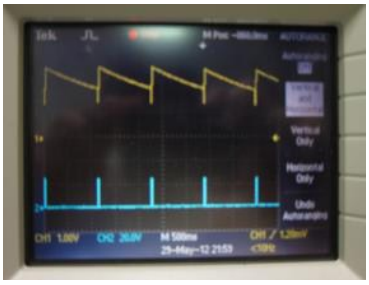
(a) ModelSim Waveform



(b) SignalTap-II Waveform

Fig. 7 Waveform of SEL-UID command-response

In Fig. 7, we measured the output waveform of high-voltage converter and its triggering pulse for the TENS that contains the tap and push waveform. Fig. 7 (a) shows the tap waveforms, and Fig. 7 (b) the push waveform. The output voltage can be in the range of between 30V and 150V according to the density of charging pulse that not showing in the waveform, the higher density of charging pulse the higher voltage it will be. The intensity of stimulation pulse is proportional to output voltage and the stimulation rate is depends on the trigging pulse. From the waveform some details can't be found due to the trade-off of memory size and sampling frequency of the scope. However, the waveform's behavior is just corresponding to our expectations.



(a) Voltage & Tap pulse

(b)Voltage & knead pulse

Fig. 8 Measurement of output waveform

Finally, a comparison of this implementation with traditional acupuncture (TA) and traditional electronic acupuncture (TEA) can be seen from Table 2. It is found that the NFC-TENS design allows us to combine traditional electronic acupuncture with NFC smartphone and towered to a significant result for contributing to human's popular health aids.

TABLE 2 CHARACTERISTICS COMPARISON OF THIS WORK WITH TRADITIONAL ELECTRONIC ACUPUNCTURE

	TA	TEA	NFC-TENS
Stimulate source	Metal needle	Pulse	Pulse
Implantation method	Intrusive penetration	Skin patches	Skin patches
Clinical utility	More precise	33% of Traditional	33% of Traditional
knowledge	Memorize acupuncture	Conscious pain area	Conscious pain area
Man machine interface	Operation acupuncture needles	Button & LCD	Smartphone control
Transfer function	Artificial manipulation	Circuit control	Wireless control
Penetrability	Very low	low	Very high
Create value	Low	Low	High
Treatment Function	Professionals	Manual recording	Network support

V. CONCLUSION

This paper presents an advanced application of FPGA design and implementation combined with the NFC-enabled smartphone to achieve a mobile electronic acupuncture health entity for healthcare aids. The paper shows a design of the bridging technology that how the use of FPGA rapid prototyping technology to complete ISO/IEC-14443A NFC standard protocol, and the realization of parameterized transcutaneous electrical nerve stimulator for improving traditional electronic acupuncture stimulator. As combining with the Android system, the NFC-TENS healthcare aids presents outstanding performance and user-friendly interface than traditional electronic acupuncture device. A system implementation results show that this design can improve the smartphone in the healthcare aids aspects of a value-added capability and practicality.

ACKNOWLEDGMENT

The work is to thank the Ministry of Education Advisory Office and intelligent electronics Design (IED) Alliance provides resources of healthcare plan, which makes our work team to successful completion of NFC smartphones for electronic acupuncture health production.

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