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# **CHANNELS ALTERNATIVE TO WIFI IN AUTHENTICATED KEY ESTABLISHMENT PROTOCOLS FOR MOBILE DEVICES**

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## 1 Introduction

The goal of the dissertation is to analyze the usability of channels alternative to WiFi in Authenticated Key Establishment (AKE) protocols for mobile devices. Nowadays, more often mobile phones are used to sending secret data. Every this kind of device has embedded speaker and microphone therefore we want to check whether is possible to establish session key just using sound.

Mobile devices to transfer data mainly use Internet. Disadvantage of this method is that network not always is available. In that case one can still transmit data using some another embedded components like IrDA, Bluetooth or NFC. Unfortunately not every device has these kind of accessories implemented. However, basis of handhelds is to have embedded speaker and microphone. That is why, in this dissertation, to communication between devices were chosen audio channel. Availability audio appliance and a lot of uses of this solution are main advantages. Moreover, the sound waves with appropriate, not to high sound intensity, does not penetrate through the walls. It causing that waves cannot be receive e.g. on the street when some protected data are sending in the house. Furthermore receiver as like sender do not need to known each other (unlike Bluetooth) before starting the communication. Sender just start to transmit data and receiver in the same time listen broadcast.

To authentication and key agreement between mobile devices was chosen Anonymous Mutual Authentication (AMA) protocol, created by L. Hanzlik, K. Klucznik, Ł. Krzywiecki and M. Kutylowski. AMA is symmetric, which means participants execute the same code. One of the advantage is simple to implemented, even on the devices with low power computing. It was originally designed for authenticating electronic documents, it proved to be portable Every key and encryption are sending by audio channel.

Application created on Android system will serve as proof of concept. App is called AKEBySound. Managed to determine that exist this kind of applications but none of theme are use to establishing session keys and they are not open source. To use our app is enough to have mobile phone/smartphone with software Android ( version 4.1.2 or higher ), working speaker and microphone, of course.

Dissertation is divided on X parts. The first section focus on analysis of the problem. Explain principal issues used to create the application. Due to the fact protocol is executed by audio channel the first subsection is about sound. The next one is one of the method to exchange keys on which AMA protocol base - Diffie-Hellman Key exchange. Tutaj cos o bezpieczenstwie bedzie itp. Dowod poprawnosci protokolu i takie tam.

Next chapter is about System design. In subsections are described assumptions of

project and used cases. Then is shown diagram classes

## 1.1 Problem

The problem is secure exchange keys between two parties, which have no knowledge of each other, in insecure, unreliable environment e.g. susceptible to eavesdropping.

The first known answer on this problem was published by Witfield Diffie and Martin Hellman. They have showed method to key exchange which is called Diffie-Hellman. Its strength and immunity to eavesdropping is based on Discrete Logarithm Problem. Existing computers are not able to compute session key from eavesdropped protocol transcript in reasonable amount of time.

Mentioned method is secure against eavesdropping, however it does not authenticate both parties to each other and thus does not guarantee security when adversary can take control over the channel in which the key establishment is being performed. Adversary taking control over the channel can perform Man-In-The-Middle-Attack (MITMA). MITMA is that, the adversary make connection with other parties trying to authenticate being not detected. He can manipulate of the communication pretending to be one of the party, changing or sending own messages, making them to believe that they are still talking to each other. The goal of these processes is obtain secrete key by attacker and thus decrypt and even modify all messages exchanged between parties.

Main ways to communicate between devices are e.g. Bluetooth or WiFi.

## 1.2 Authenticated Key Agreement

Authenticated Key Agreement Protocols base on public key cryptography and trusted authorities. In public key cryptography are required two separate keys where one is private and second one is public. This is the most common solution being used.

AKE protocols have to ensure that attacker can not obtain any information about session key from the protocol transcript. AKE protocols have to be resistant to exposed session transcript. Adversary should not be able to taking control over the communication channel having this knowledge.

## 1.3 Out-of-band channel

Beyond the focus of safety AKE protocol we wanted to study not typical communication channel to establish session key. Is worth to ensure that adversary will has as small as possible access to protocol transcript.

During the secure exchange data are needed two channels for communication between two parties. First channel, to establish session keys, should be very difficult to spy and taking over control for adversary. The second channel can be insecure because established session key should ensure that content of protected data intended for one of the parties can be encrypt only by the party participated in protocol. For the key establishment in our work was chosen sound channel, second channel is wireless.

### 1.4 Related work

## 2 Analysis of the problem

In this section we will focus on problem of establishing secure connection in insecure channel between two parties. At first the parties need to authenticate each other and then create common session key, which will be needed to symmetric encryption of the communication. We describe the adversarial model where is assumed that each of the parties secretly holds a long-term private key that enables unique authentication of this party. There is also a trusted mechanism for binding identities with public keys. The private and public key with proper length are bounded in such way that obtain private key from public key is impossible. The communication channel can be completely controlled by an adversary that can intercept, delete, delay, modify or inject messages at will. There is a relation between the requirements of the security model and a well-defined attack scenario. In the second part of this section are described necessary issues to create sound channel.

### 2.1 Security Model

There is no one ultimately defined security model for key exchange. However, we will recourse to the requirements as most fundamental for secure key exchange protocol which H. Krawczyk presents in [11].

- Authentication - each party participating in KE needs to uniquely verify identities of other authenticating party.
- Consistency - two parties participating in KE, after establish of session key have to believe that were established common session key with party which participate in protocol. In other words, Alice has to believe that she established session key with Bob and Bob has to believe that he established session key with Alice.
- Secrecy - if two honest parties established session key then third party should not be able to obtain information about this session key. Third party, which watching and interfering with the protocol run, should not be able to distinguish session key from a random key.

### 2.1.1 Adversarial Model

Is needed to consider scenario where adversary learns some secret information from parties participate in protocol. The worst case is when adversary obtain the long term secret key from one of the party. Having this key adversary can totally control this party. Then this party is as corrupted. This lead to belows property of the KE protocol.

- Real-or-Random - this is some kind of game on which basic session key security is based. When uncorrupted parties with successful end the protocol then is determined bit  $b$  at random. If  $b = 0$  the adversary get the real session key, if  $b = 1$  he receives a random value with the same length as the key. Now adversary has to output his own bit  $b'$ . If  $b' = b$  then adversary wins the game. When the adversary wins the game with probability  $P = 1/2 + \epsilon$ , where  $\epsilon$  is negligible function then the basis session key security is achieved.
- Perfect Forward Secrecy (PFS) - is the property which ensure that adversary cannot learn session keys when one of the long-term private key is compromised in the future.

Above criteria ensure for key exchange protocol that they are resistant to attacks like known-key attacks and replay attacks [8]. For some KE protocols are needed additional requirements e.g. Identity protection - identities of authenticating parties cannot be learn by an adversary.

## 2.2 Analysis of out-of-band channels

There are a lot of techniques to transfer secret data between devices. The most popular are e.g. Bluetooth or WiFi, but not every device has these kind of appliance. Additionally these techniques are vulnerable to attacks which are hard to detect. Participate parties in protocol are not able to say that someone is manipulating their session, hijacking messages or changing them. They do not even know that sent data reach appropriate party.

Safety channel could be for example two devices connected by wire. For the third party would be very difficult to eavesdrop the session. Attacker should be connected also to this wire but it would be visible for the other parties and easily to detect him. Unfortunately, carrying additional cable every time when the parties want to establish session key is inconvenient.

The other possibility could be optical channel. Sharing data using e.g. QR codes is also interesting way to authentication of devices. Attacker would have difficult task to manipulate shared data if e.g. two devices are covered by some walls. However, not every device has camera with appropriate quality that can read QR codes with appropriate big public keys.

Another way is to use vibrations []. New smartphones have installed sensor of vibration so it is possible to create such a communication channel. Attacker to manipulate this kind of channel has to generate own vibrations and it would be easily detected by authenticating parties.

Sound channel is also one of the options. Every mobile device have speaker and microphone, so we do not need to worry about no available Internet or that the other party has not installed Bluetooth or IrDA. Using ultrasound, the signal will be not detected by humans ear. Additionally mobile phones cannot generate these waves with big intense, so transferring data should be done on small distance. Of course sound channel could be easily to manipulate. Attacker with proper speaker can generate frequencies which could disturb the communication. However, he needs to be close to the authenticating parties if generated ultrasound has to be detected by party's mobiles microphone or generate sound waves with big intense which could be audible for human.

### 2.3 Sound channel parameters

Using Diffie-Hellman key exchange and asymmetric cryptography should be use the longest key length as possible. In NIST specification SP 800-131 is mentioned that recommended key length is 3072. However, in our prototype we used 1024 key length. The reason is low speed of transferring data, which is 200b/s. Decreasing time of sending one character had influence on analyzing received data. It have been taking too long time (frequency of getting data increased, so algorithm did not follow in analyze so much data in short time).

Sound channel is secured against active attacks. Adversary needs to be close to communicated party or he needs to generate ultrasound with high intense which can be detected by human, it would be heard as squeak.

### 2.4 Proposed usage of out-of-band channel

Lets assumed that Alice and Bob want to establish a secure connection between their mobile phones using sound channel. To be sure that every high frequency will be detected, they try to put their phone in a such way that microphone is as close as possible to speaker of the second phone and vice versa. Usually the speaker and microphone are set at the bottom of device, so mobile phones should be directed bottom to each other. Sound waves are spreading, so worth is protect against it. Good choice are boxes build in lead. Lead does not pass the waves, so attacker could have more difficult job to obtain protocol transcript. To obtain session key is processed AKE protocol. After this process further exchange of data can be done by WiFi, because of the speed of transferring data which is higher.



- Alice and Bob put their devices into the lead box. Both mobile phone are listening for the first sign. The first one which start generated sound wave will be initiator. For the best quality of transferring data mobiles should be directed bottom to each other no more than couple of millimeters.
- Alice decided to be initiator of the protocol. She says "Start" to the little hole in the box and her phone, after recognized her voice, start sending first data.
- Protocol is divided on couple of phase. First phase is sending ephemeral key by initiator (in our case by Alice) to the receiver. Each phase takes couple of seconds. Every data are encoded in sound waves with appropriate frequencies.
- Bob's phone uses its microphone to obtain the data sent by Alice's device.
- When phase is over, follow switch of the roles. Now Alice's phone will listening and Bob's phone sending data.
- Alice's device will receiving and decode it.

Anonymous Mutual Chip Authentication (described in detail in section 3) should ensure that even if some transferring data eavesdrop then adversary will do nothing with this data. Duration of the protocol is about 40 second - more information about duration and performance are described in section 5.

## 2.5 Microphones and speakers in mobile devices

Specification of this appliances are very different and depends on devices. During the tests could be seen that microphone from more expensive SAMSUNG Galaxy Tab is better than microphone from LG Swift L9. SAMSUNG could detect higher frequency. However, microphone from LG Swift L9 was completely enough to registered sufficiently large frequencies. Speakers also are a little different, but they have no problem to generate opportunely frequencies.

## 2.6 Anonymous Mutual Authentication protocol - Description

To establish session keys we used in our prototype Anonymous Mutual Authentication protocol which base on Diffie-Hellman key exchange. This protocol have never been implemented on the mobile phone with system Android.

AMA originally was designed to anonymous authenticate between smart cards. Is characterized by properties:

- Forward Security - if long term keys of one of the authenticating parties compromised then established session key does not reveal.

- Simultability - is possible to create protocol transcript between parties without interacting with them
- Undetectability - having protocol transcript one cannot confirm that process really took place
- Privacy - eavesdropping adversary cannot tell about identity of parties performing the protocol
- Deniability - no one of the parties cannot convince third party that he participate in protocol.

Alice		Bob
$x_A$ - private key $y_A = g^{x_A}$ - public key $cert_A$ - certificate for $y_A$		$x_B$ - private key $y_B = g^{x_B}$ - public key $cert_B$ - certificate for $y_B$
MAIN PROCEDURE		
choose $a$ at random $h_A := H(a)$ $c_A := g^{h_A}$	$\xrightarrow{c_A}$ $\xleftarrow{c_B}$	choose $b$ at random $h_B := H(b)$ $c_B := g^{h_B}$
$K := c_B^{h_A}$ $K_A := H(K, 1), K_B := H(K, 2)$ $K'_A := H(K, 3), K'_B := H(K, 4)$ $r_A := H(c_B^{x_A}, K'_A)$	$\xrightarrow{Enc_{K_A}(cert_A, r_A)}$ $\xleftarrow{Enc_{K_B}(cert_B, r_B)}$	$K := c_A^{h_B}$ $K_A := H(K, 1), K_B := H(K, 2)$ $K'_A := H(K, 3), K'_B := H(K, 4)$
check $cert_B$ , proceed with random values if $r_B \neq H(y_B^{h_A}, K'_B)$ $K_{session} := H(K, 5)$		check $cert_A$ , proceed with random values if $r_A \neq H(y_A^{h_B}, K'_A)$ $r_B := H(c_A^{x_B}, K'_B)$  $K_{session} := H(K, 5)$

Figure 1: Protocol description - Anonymous Mutual Authentication. Figure from source [12].

Scheme of protocol is shown at the 1. In scheme are use the following notation:

- $Enc$  is a symmetric encryption function.  $Enc_K(M)$  means encryption of  $M$  using key  $K$ .
- $H$  is a cryptographic hash function.
- For confirming public keys are using digital certificates and public key infrastructure (PKI).

Protocol is very simple to implement. AMA is defined a cyclic group  $G$  where Computational Diffie-Hellman Problem (CDH) is hard. At the beginning, parties (Alice and Bob)

generate their private key -  $x_A$  (respectively,  $x_B$ ) and public key  $y_A = g^{x_A}$  (respectively,  $y_B$ ). Then starts main procedure. Parties generate their ephemeral keys. Private is  $h_A := H(a)$  (where  $a$  is a random number) (respectively  $h_B, b$ ) and public ephemeral key  $c_A := g^{h_A}$  (respectively  $c_B$ ). In the first phase parties exchange ephemeral keys, based on Diffie-Hellman key exchange.

When parties obtain ephemeral public key of another party, they start compute master key  $K$ . Four different one-time keys are establish by hashing  $K$  and number parameter - different for each one-time key.

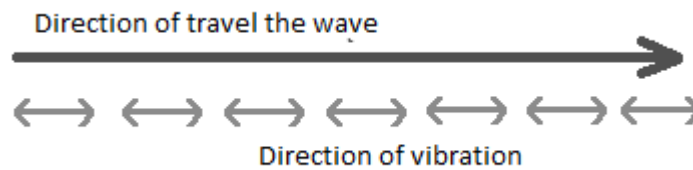
Authenticated party is raising ephemeral public key  $c_B$  (respectively,  $c_A$ ) to power of private key  $x_B$  (respectively,  $x_A$ ). On this base authentication. Verifier compute the same value without private key but with the discrete logarithm of  $c_A$  (respectively,  $c_B$ )  $((y_A)^{h_B})$ .

## 2.7 Security analysis

The key exchange protocol have to ensure that even eavesdropping data will be not useful for eavesdropper or

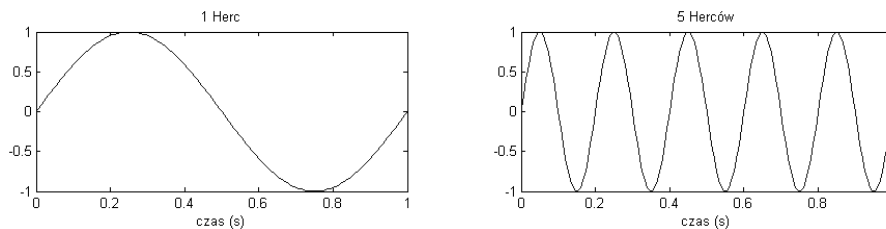
## 2.8 Sound

Sound is acoustic wave propagating in different substances such as water, air (so called vibrating wire). These are waves which cause auditory sensation and at the same time in appropriate amplitude and frequency are not detected by human organ of hearing. Sound to spread need to has some medium, that is why not propagate in vacuum. Furthermore, sound is longitudinal waves, which means that particles of the medium is in the same direction as the direction of travel of the wave.



### 2.8.1 Frequency

Audio frequency is measured in hertz (Hz), where 1 Hz means one cycle per second. Below figures show graphs of audio frequency 1 Hz and 5 Hz.

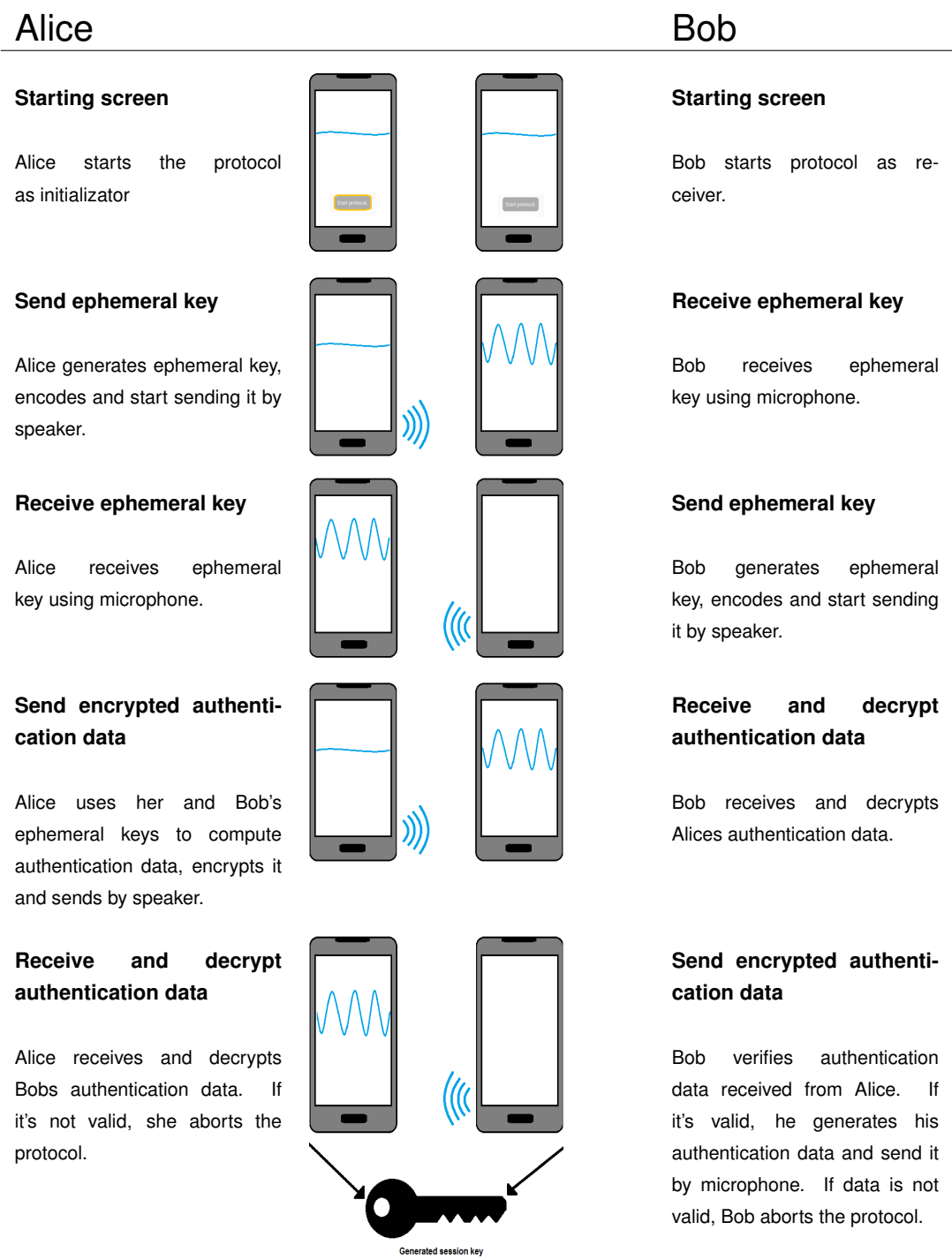


Exist three division of sound as to frequency:

- Infrasound - frequency is lower than 16 Hz.
- Hearable sound - frequency is greater than 16 Hz and lower than 20 kHz.
- Ultrasound - frequency is greater than 20 kHz.
- Hipersound - frequency is greater than 10 GHz.

Frequency specify also pitch of sound. A high frequency sound wave corresponds to a high pitch sound and low frequency sound wave corresponds to a low pitch sound.

Table 1: blablabla



### 2.8.2 Sound intensity

Loudness of the sound is dependent to his intensity. It is expressed by  $W/m^2$  unit. This is ratio the power of the acoustic wave to surface area to which wave energy falls perpendicular during 1 second [4]. Human's ear works in such way that doubling intensity of sound, do not cause that human hear it two times louder. Human hears its logarithmized value. Logarithmized measure of sound intensity is called sound intensity level. Is measured in decibels and is given by [6]:

$$L = 10 \log_{10} \left( \frac{I}{I_o} \right) [dB], \quad (1)$$

where:

- $L$  - Sound intensity level.
- $I$  - Sound intensity.
- $I_o$  - Contractual value of the intensity which determines hearing range, which is  $10^{-12} \frac{W}{m^2}$ .

### 2.8.3 Speed of sound

Speed of sound depends on center through which wave passes. Influence on speed has also temperature of the center. The slowest moves in the flue. In the air with  $20^\circ$  temperature reach in approximation 343 m/s (1230 km/h). In water with the same temperature speed is 1482 m/s (5335 km/h). The fastest sound spread in solid. For example in steel reach about 5960 m/s (21460 km/h) [7].

### 2.8.4 Ultrasounds

The present app largely, to sending data, uses ultrasound. Ultrasound are sound waves, which are inaudible for human, on the grounds of their too high frequency. Have adopted that ultrasounds starts from 20 kHz, but really everything depends on how good hearing human has. Children hear the highest frequencies. Increasing age the upper limit of hearing descend [13]. Ultrasounds end at frequencies of several GHz, where hipersounds start. Contractual it is 10 GHz. Ultrasounds have many applications. Using them one can detect objects and specify distance to them. Are used in medicine where whereby ultrasonography (USG) we can find not available for human eye diseases, watching e.g. internal organs.

## 2.9 Fourier transform

By Fourier transform one can change function  $f(x)$  in time domain to  $F(s)$  in frequency domain. In other words, distribute the function  $f(x)$  to series of periodic functions, in such

way that show how frequencies consist of the function  $f(x)$ . The formula for the Fourier transform looks as follows:

$$F(s) = \int_{-\infty}^{\infty} f(x)e^{-i2\pi xs} dx. \quad (2)$$

Sum of three functions with frequencies 3m 7m and 11 Hz on a graph:

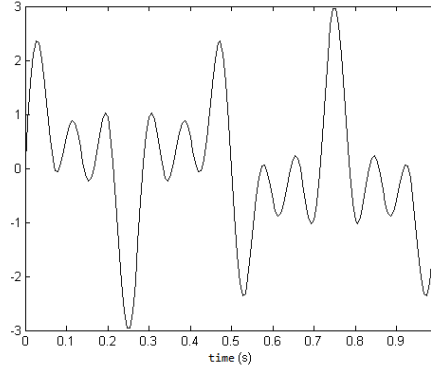


Figure 2:  $f(x) = \sin(2\pi \cdot 3t) + \sin(2\pi \cdot 7t) + \sin(2\pi \cdot 11t)$ , where  $t$  is current time.

Passing function  $f(x)$  from figure 2 through Fourier transform we will get the following graphs:

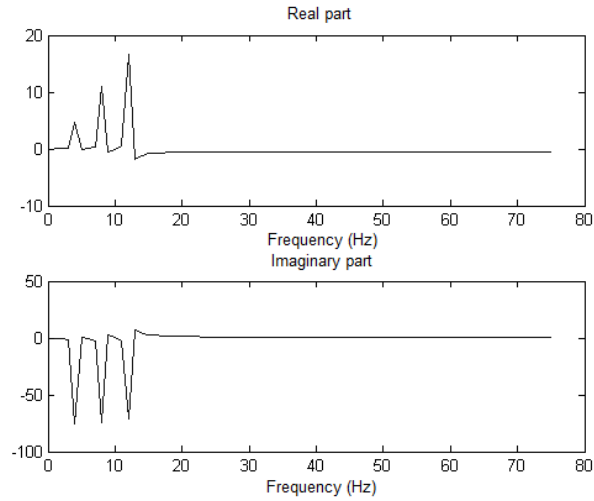


Figure 3: On the top real part results of Fourier transform, on the bottom imaginary part.

As you can see on above figure, time domain was changed on frequency domain. On graphs are bigger values for frequencies which had summed functions.

### 2.9.1 Discrete Fourier Transform

Application analyzes periodically finite number of samples of sound. To converse to frequency domain is used Discrete Fourier transform (DFT). Input samples are in the form of complex numbers, but in practice used only real numbers. Output samples are complex numbers. The following graphs show continuous signal and discretized signal [1]:

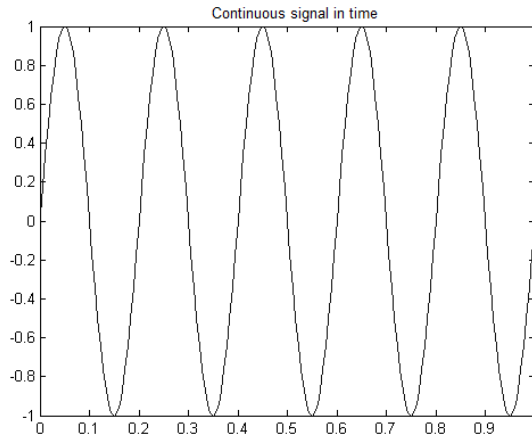


Figure 4: Continuous signal in duration 1 second.

For  $N$  signal samples  $(x_0, x_1, x_2, \dots, x_{N-1})$ , discrete Fourier transform gives series  $X_k$  for  $k = 0, 1, 2, 3, \dots, N-1$  using notation [1]:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi \frac{k}{N} n}. \quad (3)$$

Computational complexity this notation is  $O(N^2)$ , because for  $N$  elements  $X_k$  series compute sum for  $N$  samples [10].

### 2.9.2 Fast Fourier Transform

Computational complexity of discrete Fourier transform is not enough to fast process more data. Therefore developed a lot of algorithms, which improve its calculation. Exist algorithms, which do discrete Fourier transform having computational complexity  $O(N \log N)$ , where for large number of data is significant improvement. They use design paradigm divide and conquer. Precursors of these solutions are James William Cooley and John Tukey, who



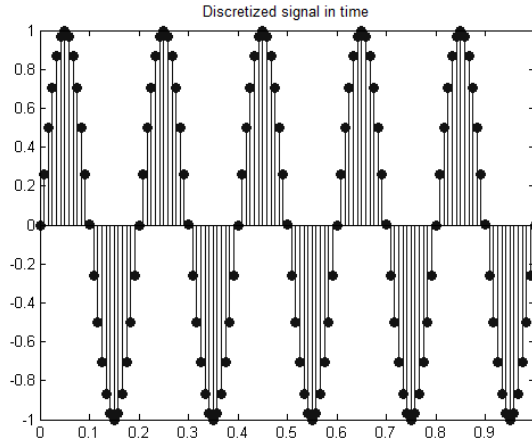


Figure 5: Discretized signal in constant time period. In this case in 1 second are 121 samples.

elaborated first faster algorithm to compute DFT, known as fast Fourier transform (FFT). It is worth mentioning that FFT is not approximate value of DFT. FFT returns the same values but do this much faster.

### 2.9.3 Hanning window

Window functions are functions which are used with DFT. Often during process of DFT occur blur of spectrum, which mean that on the spectrum are seeing values for frequencies different than the real frequency of signal. To minimize this effect are used window functions. In time domain it is multiply every sample of signal by corresponding value of sample of window. The simplest window is rectangular window. Spectrum of this windowing is shown in 6

In our protocol is used Hanning window which is noticed by:

### 2.10 Pulse-Code Modulation

Pulse-Code Modulation (PCM) is a method used to digitally represent sampled analog signals. PCM is based on representation of the instantaneous value of the signal (Sampling) at uniform intervals (sampling rate). The sampled analog data are represent by binary data. During the demodulation, sample rate should be at least two times greater that frequency of receiving analog signal (greater than the Nyquist frequency  $f_s/2$ ). This ensure that sampled values represent analog signal without errors. In our prototype sample rate is 44,1 kHz. The highest frequency which we use in application is about 20,5 kHz so 44,1 kHz is sufficient.

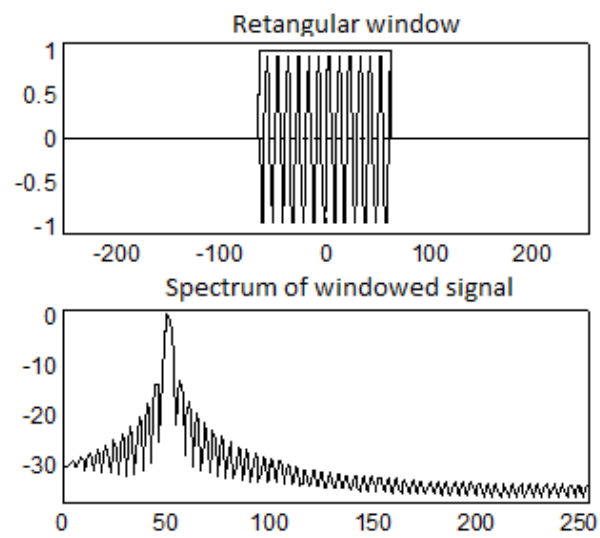


Figure 6: Rectangular window and its effect in spectrum of signal.

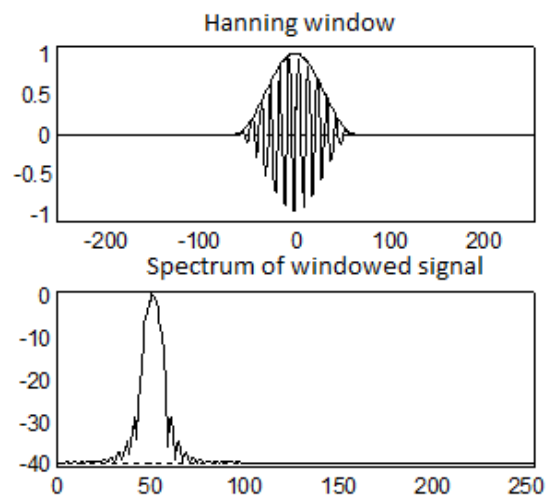


Figure 7: Hanning window and its effect in spectrum of signal.

## 3 Prototype Design

### 3.1 Mobile Devices

AMA attempts to be simple in implement and does not require high-power computing. So it is ideal to implement it on chip cards. Due to the fact the chip cards are slowly replacing by mobile phones we have decided to implement AMA on this devices. Operating system which we have chosen is Android, because it is one of the most frequently used software on mobile phones. The lowest version, for which program should work without problems is Android 4.1.2. Core of the AMA was implemented in C++. Sound channel and layout was made using Android's libraries.

### 3.2 Operating System

Operating system which was chosen is Android version 4.1.2 and higher. This is the newest version which was available for device which has been using in tests. Second device to tests has Android 4.2.2. This software has every required libraries whereby is possible to create sound channel between two devices (AudioTrack and AudioRecord). Additionally, Android allows to use of modules written in C++.

### 3.3 Security of Android

The operating system should ensure that running application cannot interact with another. Each application is run in separate process having own user ID. This sets up a kernel-level Application Sandbox, where by default application cannot interact with each other and has limited access to OS.

Furthermore, every application has to be signed by developer. Applications without signature will be rejected by Google Play or the package installer on Android device. Signed certificate is verified by Package Manager after installation of application.

### 3.4 Application architecture

Application consists of three parts: cryptographic module, sound channel module and graphic interface. Cryptographic module is written in C++ and to use it in Android, was needed to write a wrapper using JNI (Java Native Interface). NDK (Native Development Kit) is a toolset that allows to add native-code languages such as C and C++ to Android's app. User interface consists of initial screen where user chooses which frequencies have to be used during sending data. In next screen is dynamic graph with recording sound wave and button which starts the protocol. To show sound as sinusoid wave we used external library AChartEngine, the rest of interface is created by standard Android's libraries.

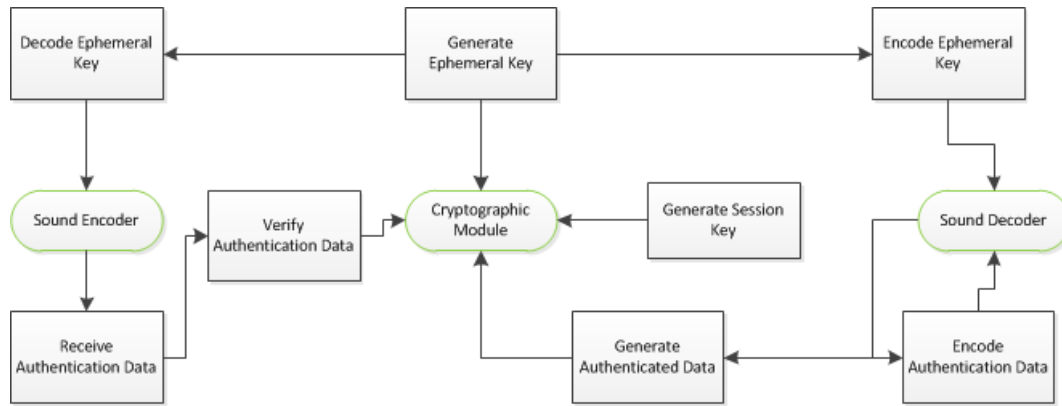


Figure 8: Application architecture.

### 3.5 Cryptography library

Exist few of cryptography libraries which are written in Java (e.g. javax.crypto, BouncyCastle), but we wanted to create cryptography module which is independent of the platform. The choice fell on CryptoPP. It is free, open source cryptography library written in C++. The library is objectives and very easy to use. Ensures symmetric and asymmetric cryptography along with signatures and secure hash function. Is used by such companies as Microsoft or Symantec.

### 3.6 Activity diagram

### 3.7 NIST recommendation for security parameters

NIST recommends using 3072 bit length keys to ensure low probability of calculating discrete logarithm. This length is set as default in CryptoPP, however in our prototype we are using 1024 bit. It is caused by duration of sending data by sound. Now, sending 1024 bit length keys take some time and for needs of presentation we decided to stay with this length. For more information please check [5].

### 3.8 Shared cryptographic module

Cryptographic module is designed in such way that it will be easy to use it on different platforms. Application treat it as a black box where are exchanging strings with data. Implementation is made in C++ based on DiffieHellman and Authenticated-DiffieHellman classes from Cryptopp library. It performs following cryptographic operation:

- Modular exponentiation

- Long term and ephemeral key generation (Diffie-Helman)
- Certificate generation and verification
- Secure hashing (SHA1)
- Symmetric encryption (AES)

Core of this module is class `MutualAuthenticationChip`. It is responsible for inputting, preparing and outputting data to Application. All sensitive data is kept internally using secure byte blocks. Messages generated in the protocol are converted to strings. For group arithmetic operations and modular exponentiation we use build in `Integer` class provided by the library.

The overall implementation tightly follows the protocol specification and the only overhead is connected with conversions to provide compatibility with the rest of the application.

```

1  void KeyGenerator::GenerateEphemeralKeyPair(CryptoPP::RandomNumberGenerator &rng,
      byte *privateKey, byte *publicKey) const
2  {
3      Integer a = Integer(rng, keySize);
4      byte *aEncoded = new byte[keySize];
5      a.Encode(aEncoded, keySize);
6      privateKey = HashClass::getSHA1(aEncoded, keySize);
7      CryptoPP::Integer exponent(privateKey, keySize);
8      CryptoPP::Integer cA = a_exp_b_mod_c(g, exponent, p);    //ca = g^H(a)
9      cA.Encode(publicKey, keySize);
10 }
```

Listing 1: Example of CryptoPP usage for ephemeral key generation.

### 3.9 Java Native Interface - C++ Wrapper

To be able to use cryptographic part written in C++ in Android, we had to create C++ wrappers using JNI (Java Native Interface) [2]. Main class which communicate with C++ code has native methods, for which, after appropriate compilation, was created `MACWrapper.h` where definition of methods looks like below.

```

1  /*
2   * Class:      com_example_androidake_MutualAuthenticateChip
3   * Method:     prepareMACCPP
4   * Signature:  (Z)V
5   */
6  JNIEXPORT void JNICALL
      Java_com_example_androidake_MutualAuthenticateChip_prepareMACCPP
7      (JNIEnv *, jobject, jboolean);
```

Listing 2: Example of JNI usage for method definition.

Implementations of methods are in `MACWrapper.cpp`. There are made conversion from C++ data type to Java data type and vice versa.

```

1  JNIEXPORT void JNICALL
    Java_com_example_androidake_MutualAuthenticateChip_prepareMACCPP
2  (JNIEnv *env, jobject thisObj, jboolean jinit) {
3      bool init = jinit;
4      if(init == true) {
5          mac = new MutualAuthenticationChip(init);
6      } else {
7          mac_B = new MutualAuthenticationChip(init);
8      }
9  };

```

Listing 3: Example of JNI usage for method implementation.

### 3.10 Base64

One of the biggest problem was decided in what representation data should be sending. First choice was standard binary representation with 0 and 1. During creation of sound channel we have found that sending one ephemeral key, which has 1024 bits will take too long. So we decided to reduce sending data using Base64 conversion. Six bits are transform to one of the 64 defined signs. Hence, instead of sending 1024 sings we send just about 172. Data which come from cryptographic module are in Hexadecimal representation. To converse we have used library created by Robert Harder [9].

```

1  public static String fromHexToBase64(byte[] hex_byte) {
2      String hex_str = ConverterJava.ByteToString(hex_byte);
3      byte[] decodedHex = null;
4      try {
5          decodedHex = Hex.decodeHex(hex_str.substring(0,
6              hex_str.length() - 1).toCharArray());
7      } catch (DecoderException e) {
8          e.printStackTrace();
9      }
10     String encodedHexB64 = Base64.encodeBytes(decodedHex);
11     return encodedHexB64;
12 }

```

Listing 4: Example of code converting from Hex String to Base64 String

### 3.11 Sound channel

Sound channel was one of the most difficult part during creation of application. One of the reason was inaccessibility of library whereby we could transform received sound data to cryptographic data. Whole process of analysis received data had to be created from beginning. At beginning we had doubt about sensitivity and precision of speaker and microphone in mobile devices. Especially when we wanted to use ultrasonic waves which could be hard to interpreter. Fortunately, doubts were dispelled after first testing of this channel. Results of working will be describe in Test section. Here we focus on principle of operation.

### 3.11.1 Generating sound wave

Class responsible for generating sound wave get data presented in Base64 (Check section with Base64). Every character A-Z, a-z, 0-9, + and / is mapped to one of the 64 frequencies.

A = 10 kHz,

B = 10,15 kHz,

C = 10,3 kHz,

...

/ = 19,55 kHz

Additional two characters "," and "." represent begin of data and end of data. Sample rate is 44,1 kHz. Every character is sending during 30 ms, which means that for each pitch is needed 1323 samples. To create sinus wave each sample for  $i \in (0, 1322)$  is calculating by formula:

$$\sin\left(\frac{\text{Frequency} * \pi * 2 * i}{44100}\right)$$

These samples are processed by AudioTrack library to sound using PCM encoding.

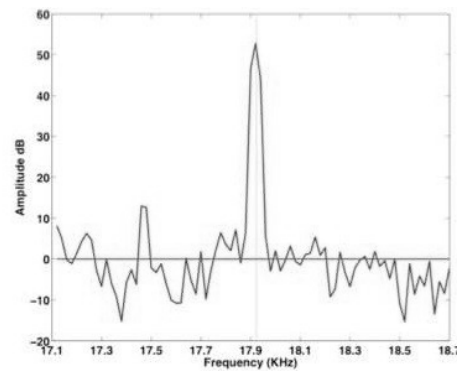
### 3.11.2 Receiving sound

Retrieving sound is more complicated than sending. In separate process, using AudioRecord library, in every 15 milliseconds (if sending of one character takes 30 ms), are taken samples and then, as one buffer, are appended to array of buffers. Separate process, in the same time, takes first buffer from array and analyses it.

At this moment, the samples are as short integer values which represent sound in time domain (sinusoid). To check in which frequency was received sound is needed to convert the sampled function from time domain to the frequency domain. We used to this Discrete Transform Fourier. Library which we have chosen to run DFT is [3].

Before change of domain, we need to window samples, using Hanning windowing. Thereby, chart in frequency domain is more readable and is easier to find the place with the highest pitch. Windowed samples are put into DFT method and on the output we have result in frequency domain. The effect on the graph looks like at 3.11.2.

Now, algorithm tries to find the highest place in the output. The reason of getting data in two times shorter time than sending one character is that, in one buffer can be two frequencies. In the worst case, algorithm can find one frequency in three buffers in a row, even if in first and third buffer was also another frequency, but because of lower sound intensity or less samples representing this frequency, would not be found as a highest pitch. Dividing time of receiving by two ensure that always, at least once, expected frequency will be registered. If he finds pitch with amplitude higher than 50, for frequency lower than 14 kHz, or 10 for higher than 14 kHz (this different follows from the smaller volume for the higher



frequency by hardware limitation) is checked whether caught frequency is in our dictionary (with margin of error  $\pm 50$  Hz).

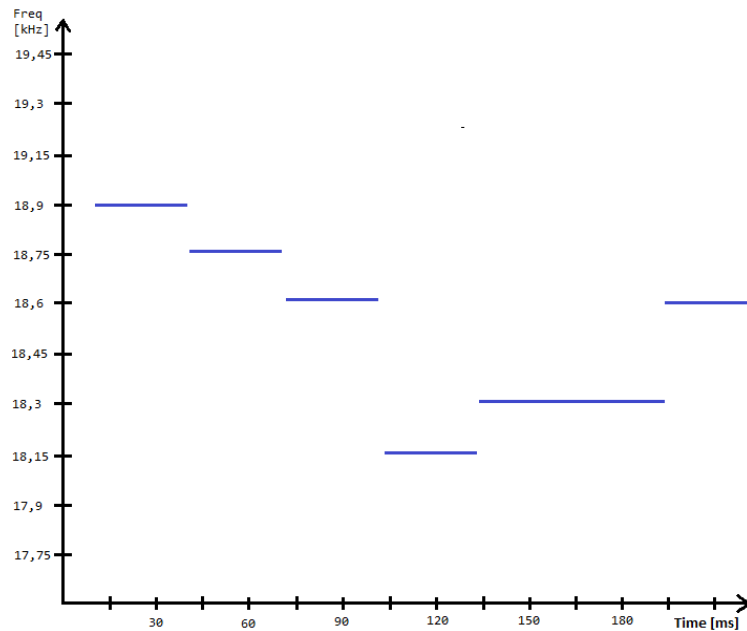


Figure 9: Figure show received frequencies in time.

Caught value is put to the memory and wait for the next result. If current frequency is different than before we change the previous frequency to one of the 64 signs. Otherwise we increment the counter. If counter gain value three (maximal number of occurrences on received character in three further buffers), counter is reset and return adequate character.



## 4 Tests

To all tests was used two devices: LG Swift L9 with system Android 4.1.2 and tablet Samsung GALAXY Tab 2 with Android 4.2.2.

### 4.1 Receiving data in sound channel

During tests we have focused on below factors:

- Distance between devices.
- Position of devices terms of placement of speaker and microphone.
- Distance between chosen frequencies.
- Working during sounds in the background.
- Sending characters in shorter time than 30 ms.

Firstly, we have tested distance between chosen frequencies. Every character from Base64 coding is mapped to appropriate frequency. The smaller distance then is possible to use higher frequencies. We have choose three spaces:

- 150 Hz. The lowest frequency 10,5 kHz, the highest - 20,25 kHz.
- 130 Hz. The lowest frequency 11,8 kHz, the highest - 20,25 kHz.
- 100 Hz. The lowest frequency 13,8 kHz, the highest - 20,3 kHz.
- 100 Hz. The lowest frequency 14 kHz, the highest - 20,5 kHz.
- 100 Hz. The lowest frequency 14,3 kHz, the highest - 20,8 kHz.

We did not want to go below 10 kHz and higher frequency than 20,5 is hard to detect for mobile phone (especially for LG). Distance 100 Hz is the smallest to test because of implemented algorithm. During the tests, proved to be that for almost every test cases, protocol was successful in 70%. Except the last one always end by failure. Character which represent end of sending data has always the highest frequency. In this case it was 20,8 kHz. Only LG Swift cannot registry that frequency. Samsung dealt with it flawlessly.

There are several reason why the result was not 100%. Sometimes, if we send, for example, frequency 20 kHz then second device receive it as 19,9. It can be caused by some distortion on the microphone on even on the speaker. What happened was that the speaker make sound different than usual. Was needed restart of device. Sometimes it is sufficient that one of the device froze on some milliseconds and then receiving device lose some characters.

Measure of allowed distance between devices we have started with stick microphone from LG with speaker from Samsung. This gave us the best results. Received amplitude was the biggest, hence easier, for algorithm, was to find interesting for us frequency. Then we increase distance to 2 cm. In this case results was also good. Sessions keys was established almost every time. Problem was started increasing distance to 6 cm. Bigger frequencies was not registered by microphone.

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