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Embedded service oriented microcontroller architecture.

Extensible client-server communication architecture for small devices

Master thesis

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Author's Declaration

This work is composed by myself independently. All other authors' works, essential states from literary sources and facts from other origins, which were used during the composition of this work, are referenced.

Signature of candidate:

Date:

Acronyms

API Application programming interface. 7

FTP File Transfer Protocol. 9, 10

HMI Human Machine Interaction. 5

HTTP Hypertext Transfer Protocol. 5, 10

RPC Remote procedure call. 8

SMTP Simple Mail Transfer Protocol. 10

SOA Service-oriented architecture. 5, 7, 8

SOAP Simple Object Access Protocol. 5, 10

UDDI Universal Description, Discovery and Integration. 9, 10

WSDL Web Services Description Language. 5, 10

XML Extensible Markup Language. 5, 10

Annotation

Current work introduces conceptual approaches for implementing an extensible service oriented client-server application on a small microcontroller. This is a general-purpose transport and hardware independent embedded server that uses remote procedure calls as primary communication protocol. This server looks like remote service that could provide defined functions to the client. ...

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1 Introduction

Computers are very essential in our life. Computer is an electronic device used in almost every field. It is very accurate, fast and can accomplish many tasks easily. In early days computers were only used by the government and army to solve different high computational tasks. After invention of low-cost microprocessors, computers became available to every person. Nowadays there are billions of personal computers and they are almost at every home.

Present day computers may be divided into two groups: very big and very small systems. In one group are mainly servers and server farms, and in the other are mainly embedded systems. The gap between these groups becomes more wider, because of the availability of new small and low-power devices, which computational power raises constantly. Lot of people prefer now to buy a tiny laptop instead of traditional workstations with a monitor and computer case under the table. There is also a more smaller group of devices, that are implemented for a particular purpose - embedded computers. Every home has several examples of embedded computers. Any appliance that has a digital clock, for instance, has a small embedded microcontroller that performs no other task than to display the clock. Modern cars have embedded computers onboard that control such things as ignition timing and anti-lock brakes using input from a number of different sensors.

Today, there is very little or no communication between embedded devices and large servers in the web. The problem is not only in the communication infrastructure, because the current communication technologies are able to provide different wired and/or wireless connections. The problem is how we design and implement embedded systems. While we try to keep big systems as open as possible (since it is their primary role), we tend to seclude and isolate embedded systems without providing easy ways to add a custom interface to them. Embedded systems are still mainly seen as vendor-specific and task-oriented products, and not as components that can be easily manipulated and reused.

If all classes of devices could speak the same language, they could talk directly to each other in ways natural to the application without artificial technical barriers. This would allow easily creating seamless applications that aggregate the capabilities of all the electronics. The interoperation adds value to all the devices.

One of the methods how this communication can be performed is the concept of web services. World Wide Web Consortium (W3C) defines a "Web service" as:

A Web service is a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL¹). Other systems interact with the Web service in a manner prescribed by its description using SOAP²-messages, typically conveyed using HTTP³ with an XML⁴ serialization in conjunction with other Web-related standards.

Services are unassociated, loosely coupled units of functionality. Not only large server system are capable of providing this functionality. Services can also be applicable in the resource-constrained embedded devices.

This work would introduce the concepts how SOA⁵ can be in the context of embedded systems. This contains some research of already available technologies and the implementation of small system prototype, which uses service approach.

1.1 Impact

The impact of the research in this thesis has been started during the accomplishment of internship at the university. I was worked for some company and my task was to develop HMI⁶ interface to some embedded system. We were using wireless communication between the control unit and the machine it was controlling. Control unit was a smartphone that was sending commands through Bluetooth protocol. On the other side there was a coffee machine that was receiving and executing that commands.

At the same time i was studying how large enterprise systems communicate to each other. I was reading about web services and related technologies. Then was born an idea that there could also be a "small" device network.

¹Web Services Description Language

²Simple Object Access Protocol

³Hypertext Transfer Protocol

⁴Extensible Markup Language

⁵Service-oriented architecture

⁶Human Machine Interaction

This was a research project and developed prototype could potentially become a real product. In that case it needs to be connected to existing infrastructure. Coffee machine could provide different remote services: remote coffee product prepreparing, coffee machine maintenance and acquisition of statistical data, remote payment. This could look like traditional coffee automatic machines at the streets that accept cash.

I stated to mine the information about different control possibilities. This is how this research became a topic of my master thesis.

1.2 Outline

First section will introduce the concept of web services. Then i will write about how all this technologies could be ported to a small device. Next goes the implementation of a small remote service. There are described implementation details of a server and client library.

Devices Profile for Web Services

2 Preliminaries

Internet technology is the environment in which billions of people and trillions of devices are interconnected in various ways. As part of this evolution, Internet becomes the basic carrier for interconnecting electronic devices – used in industrial automation, automotive electronics, telecommunications equipment, building controls, home automation, medical instrumentation, etc. – mostly in the same way as the Internet came to the desktops before. More and more devices getting connected to World Wide Web. Variety of factors have influenced this evolution [1]:

- The availability of affordable, high-performance, low-power electronic components for the consumer devices. Improved technology can assist building advanced functionality into embedded devices and enabling new ways of coupling between them.
- Even low cost embedded devices have some wired or wireless interface to local area networks of the Ethernet type. TCP/IP family protocols are becoming the standard vehicle for exchanging information between networked devices.
- The emergence of platform independent data interchange mechanisms based on Extensible Markup Language (XML) data formatting gives lots of opportunities for developing high-level data interchange and communication standards at the device level.
- The paradigm of Web Services helps to connect various independent applications using lightweight communications. Clients that are connected to the service and the service itself may be written using different programming languages and be executed on different platforms.
- Presence of Internet allows existing of small embedded controllers and large production servers in the same network, with a possibility to change information.

The integration of different classes of devices, which employ different networking technologies, is still an open research area. One of the possible solutions is the use of SOA software architecture design pattern.

2.1 Service oriented architecture

Service-oriented computing is a computing paradigm that uses services as basic building blocks for application development. [2]

The purpose of **SOA** is to allow easy cooperation of a large number of computers that are connected over a network. Every computer can run one or more services, each of them implements one separate action. This may be a simple business task. Clients can make calls and receive required data or post some event messages.

Services are self-describing and open components. There is a service interface, that is based on the exchange of messages and documents using standard formats. Interface internals (operating system, hardware platform, programming language) are hidden from client. Client uses only a service specification scheme, also called contract. Consumers can get required piece of functionality by mapping problem solution steps to a service calls. This scheme provides quick access and easy integration of software components.

Service architecture have been successfully adopted in business environments. Different information systems, that were created inside companies for automation of business processes, are now turned into services which may easily interact with each other. For example, Estonian government uses services to transmit data between information systems of different departments. There are also some free services available. Some Internet search companies like Google, Bing, Yandex provide lots of alternatives how to retrieve data without using regular browser(search , geolocation and maps, spell check API⁷s)

There are available many technologies which can be used to implement **SOA** [3]:

- Web Services
- SOAP Simple Object Access Protocol, is a protocol specification for exchanging structured information in the implementation of Web Services in computer networks.

⁷Application programming interface

- RPC Remote procedure call is an inter-process communication that allows a computer program to cause a subroutine or procedure to execute in another address space (commonly on another computer on a shared network) without the programmer explicitly coding the details for this remote interaction.
- REST Representational state transfer is a style of software architecture for distributed systems such as the World Wide Web. REST has emerged as a predominant web API design model.
- DCOM Distributed Component Object Model is a proprietary Microsoft technology for communication among software components distributed across networked computers.
- CORBA Common Object Request Broker Architecture enables separate pieces of software written in different languages and running on different computers to work with each other like a single application or set of services. Web services
- DDS Data Distribution Service for Real-Time Systems (DDS) is an Object Management Group (OMG) machine-to-machine middleware standard that aims to enable scalable, real-time, dependable, high performance and interoperable data exchanges between publishers and subscribers.
- Java RMI Java Remote Method Invocation is a Java API that performs the object-oriented equivalent of remote procedure calls (RPC), with support for direct transfer of serialized Java objects and distributed garbage collection.
- Jini also called Apache River, is a network architecture for the construction of distributed systems in the form of modular co-operating services.
- WCF The Windows Communication Foundation (or WCF), previously known as "Indigo", is a runtime and a set of APIs (application programming interface) in the .NET Framework for building connected, service-oriented applications.
- Apache Thrift is used as a remote procedure call (RPC) framework and was developed at Facebook for "scalable cross-language services development".
- ...

This list can be continued. Most of these technologies are inspired by idea of RPC⁸. An **RPC** is initiated by the client, which sends a request message to a known remote server to execute a specified procedure with specified parameters. The remote server sends a response to the client, and the application continues its process.

Web Services are the most popular technology for implementing service-oriented software nowadays. Next section will focus on this framework and on the main features that any **SOA** implementation should have.

2.2 Web Services architecture

2.2.1 Web Services Model

The Web Services architecture is based on the interactions between three roles [4]: service provider, service registry and service requestor. This integration has of three operations: publish, find and bind. The service provider has an implementation of service. Provider defines a service description and publishes it to a service requestor or service registry. The service requestor uses a find operation to retrieve the service description locally or from the service registry and uses the service description to bind with the service provider and invoke or interact with the Web service implementation. **Figure 1** illustrates these service roles and their operations.

⁸Remote procedure call

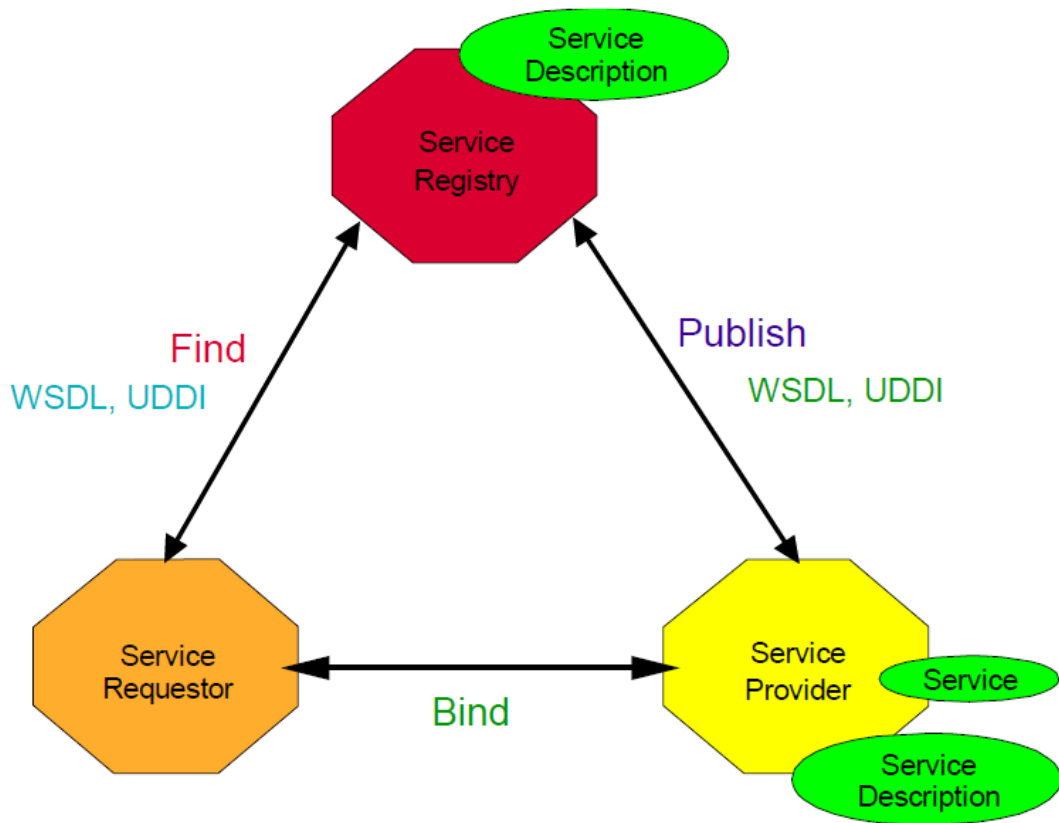


Figure 1: Web Services roles, operations and artifacts [4]

Service registry is a place where service providers can publish descriptions of their services. Service requestors can find service descriptions and get binding information from them. Binding can be static and dynamic. Registry is needed more for dynamic binding where client can get service info at the runtime, extract necessary functional methods and execute them on the server. During static binding service description may be directly delivered to the client at the development phase, for example using usual file, FTP⁹ server, Web site, email or any other file transfer protocol. There are also available special protocols, named Service discovery protocols (SDP), that allow automatic detection of devices and services on a network. One of them is the UDDI¹⁰ protocol, which is also was mentioned on Figure 1. UDDI is shortly described in **Web Services Protocol Stack** section.

Artifacts of a Web Service Web service consists of two parts [4]:

- **Service Description** The service description contains the details of the interface and implementation of the service. This includes its data types, operations, binding information and network location. There could also be a categorization and other metadata about service discovery and utilization. It may contain some Quality of service (QoS) requirements.
- **Service** This is the implementation of a service - a software module deployed on network accessible platforms provided by the service provider. Service may also be a client of other services. Implementation details are encapsulated inside a service, and client does not know the details how server processes his request.

2.2.2 Web Services Protocol Stack

WS architecture uses many layered and interrelated technologies. Figure 2 provides one illustration of some of these technology families.

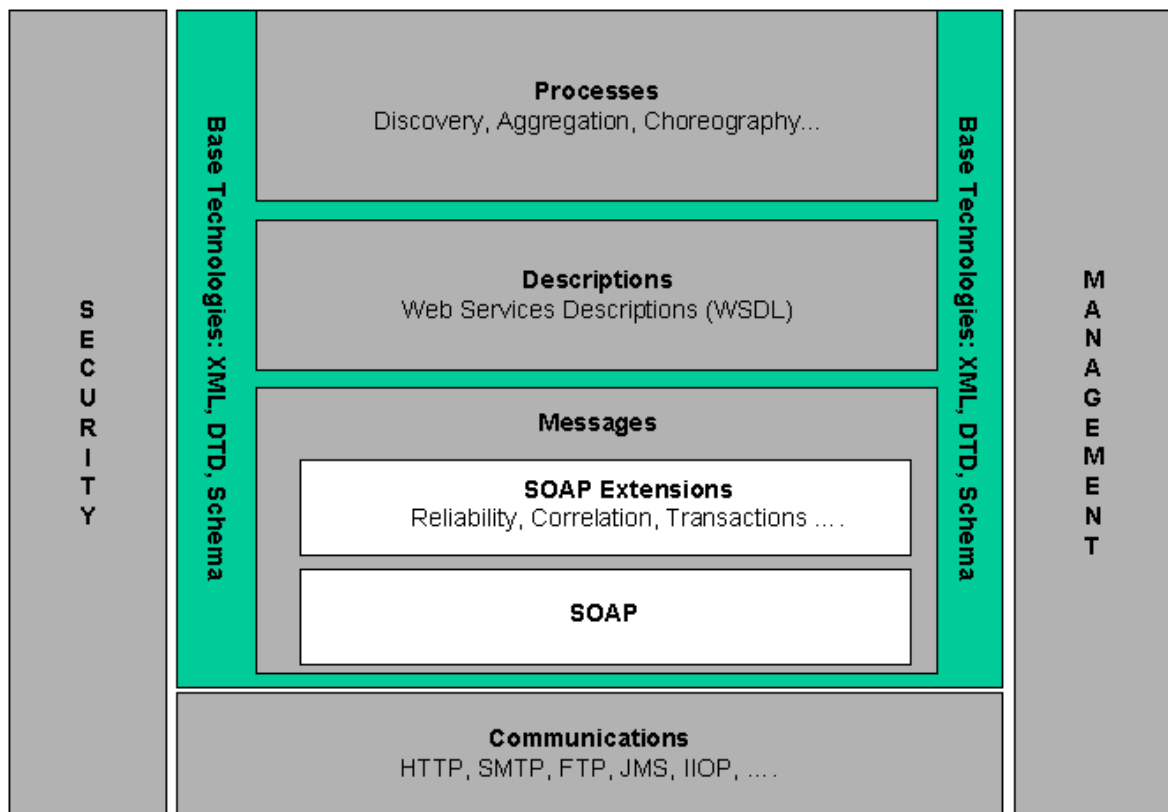


Figure 2: Web Services Architecture Stack [5]

We can describe these different layers as follows:

- **Communications** - This layer represents a transport between communication parties(service provider, client, service registry). This layer can be any network protocol like: **HTTP**, **FTP**, **SMTP**¹¹ or any other suitable transport protocol. If Web service is used in the Internet, the transport protocol in most cases will be **HTTP**. In internal networks there is the opportunity to agree upon the use of alternative network technologies.
- **Messages** - In order to communicate with a service, client should send a message. Messages are **XML** documents with different structure. **SOAP** protocol defines how these messages should be structured. **SOAP** is implementation independent and may be composed using any programming language. Protocol specification and message descriptions can be found in document SOAP Version 1.2 Part 1: Messaging Framework (Second Edition)[6].
- **Descriptions** - This layer contains the definition of service interface (see also [section 2.2.1](#)). Web Services use **WSDL** language for describing the functionality offered by a web service.

2.3 SOA and Embedded Systems

2.3.1 Authentication and Authorization in embedded systems

Need of security Authorization is the process of granting or denying access to a network resource. Most computer security systems are based on a two-step process. The first stage is authentication, which ensures that a user is who he or she claims to be. The second stage is authorization, which allows the user access to various resources based on the user's identity.

Users are essential part of every system. System should be designed with a requirement, that there will be at least one user. System without any purpose does not make sense. Usually

⁹File Transfer Protocol

¹⁰Universal Description, Discovery and Integration

¹¹Simple Mail Transfer Protocol

information systems have lots of users with different roles. There should be an system administrator - the most authorized individual in the system, managers and normal users. System should distinct them all somehow.

Another requirement is system and information security. System may contain sensitive data, that should not be available to general users. In case of remote services there are some services that are not open. These services or some of their parts are require some identity to pass through.

Let's take a usual website as example. Common website has at least three different user roles: user or guest, content publisher and system administrator. Last two roles may be joined together, but in general content publishers do not do system maintenance, they just work with content of webpages. There may be more different roles, but these are the main ones. Imagine you open a web page and you see the content. You follow the links and surf the web site. If you want to change something, for example you do not like the design or some words on web page were misspelled, you need to find special place where you can input your **credentials** and get into the system. This will happen only if you have proper **permission** to do that. When you get inside you are still not able to do anything due to lack of privileges. For example you cannot turn of the webserver or disable the your website. There may be lots of different roles and responsibilities in the system and each role has limited access to system resources.

Embedded device as a service may be similar to system example above. Device may have some limited use cases, that are not available to not authorized service clients. This may be internal information retrieving, some device manipulation functions (turn on/off something, delete/remove something from the system, change of system preferences). Some device functionality may be available only for limited people, for example system owner. The real life example of such system is the wireless router. Router clients are other computers, they can send and receive network packets. Router uses wireless security protocols, which permit unauthorized access. Even if you are connected to a secure access point, you are not able to change system settings. You should have admin permission (password) to manage the system. This kind of system, like many embedded systems, is made for one purpose. Router purpose is to provide access for the network. You also can remember lots of similar systems, that use authorized access. Nowadays it is not new to get remotely into some device and to change internals, but embedded system integrations are still not so common. Imagine near future, you are sitting at work and thinking to go home. After a long day you became really hungry. You take your smartphone and connect to your remote wireless fridge service at home. You type your password and get list of all food in your fridge. Now you know what you need to buy and the real candidates to be throwed to the rubbish bin. You adjust power in some fridge area and your beer will be very cold when you get home. Is it just a dream? Is it really hard to realize using present time technologies?

The main problem here is the security. Wired embedded network protocols are mostly not designed with security in mind. These networks were isolated from the Internet in the past. They could only be attacked using direct physical access to the network. Nowadays Internet and wireless networks are popular. Lots of communication between different systems goes through the wireless channel. Radio link is also available to your neighbour behind the wall. Generally, you do not want to broadcast what is in your fridge or to give ability to connect to your air conditioning service. Therefore you need to use some authentication scheme for your service.

Authentication protocols Authentication is any process by which you verify that someone is who they claim they are. (<https://httpd.apache.org/docs/2.2/howto/auth.html>)

Humanity has already invented a lot of different authentication techniques.

The ways in which someone may be authenticated fall into three categories: (<http://en.wikipedia.org/wiki/Authentication>)

- the ownership factors: Something the user has (e.g., wrist band, ID card, security token, software token, phone, or cell phone)
- the knowledge factors: Something the user knows (e.g., a password, pass phrase, or personal identification number (PIN), challenge response (the user must answer a question), pattern)
- the inherence factors: Something the user is or does (e.g., fingerprint, retinal pattern, DNA sequence (there are assorted definitions of what is sufficient), signature, face, voice, unique bio-electric signals, or other biometric identifier).

Authentication may be one way (only client is checked for validity) and two way (both client and server check each other). Some systems may require to use different security factors together: you say password, provide ID card and show you fingerprint There are also available many standard authentication protocols. If you start searching you will probably find similar list:

- Transport Layer Security (TLS)
- Extensible Authentication Protocol (EAP)
- Password authentication protocol (PAP)
- Challenge-Handshake Authentication Protocol (CHAP)
- Password-authenticated key agreement
- Remote Authentication Dial In User Service (RADIUS)
- Kerberos
- Lightweight Extensible Authentication Protocol (LEAP)

Choosing suitable protocol is not trivial problem. There is no any case general protocol. Most of them are designed to interconnect big computers inside a network. Mostly they operate on transport and application level and use TCP/IP protocol stack.

All these protocols could be divided into these groups:

- Protocols that transmit the secret over the network. (For example Password authentication protocol). These protocols are not secure.
- Protocols that not send secrets and provide authentication through sending messages. (CHAP and Password-authenticated key agreement).
- Protocols that require a trusted third party.

Protocols of first type have been deprecated because of security reasons. They send sensitive data over the network and everyone else between two nodes can catch this data.

Second group of protocols was invented because the first group was unable to provide proper level of security. Link between client and server (two parties) does not contain pure information about the secret. Parties use cryptography and send encrypted messages to each other. Finally they authenticate each other when there is enough information gathered to validate the authority.

Last group uses trusted third party authority to check each other. There is assumption that all three parties should have connection between each other. Embedded device during client authentication needs to connect some server and ask for a secret. Third party should always have a high authority, two other parties should trust him. This scheme should be used in case of high security requirements.

Choosing of right authentication protocol in general should depend on application. Sometimes, there will be enough just to send plain text passwords over the network. Engineer should analyze all hazards during system design process.

Lifecycle of an embedded system is more longer than lifecycle of average personal computer. Application specific controller may run for decades and it will be still functional. Chooosed security algorithm may be not secure enough after some years. Some vulnerabilities can be discovered during that period. Computational power of modern processors raises every year and secure encryption may be cracked during some seconds in the future. There is no 100% secure system, everything can be breaked.

Your system security should have such encryption, that provides proper security level to your application data and can not be cracked quickly. How quick it is depends on your data and security requirements of your data.

Another aspect is the complexity of cryptography algorithms. Embedded devices are usually small low power devices with limited computation abilities. Not every algorithm suits well. It should be quick and resource friendly , and in same time it should be secure.

Nowadays, the last versions of the Wifi and Wimax standards include the use of Extensible Authentication Protocol (EAP) declined in different versions (LEAP - EAP using a Radius Server -, EAP-TTLS, etc...). In practice, EAP is interesting for workstations or desktop computers but does not fit the needed security of particular systems such as handheld devices, short-range communication systems or even domestic Wireless LAN devices. The reason being that many versions of EAP use certificates, public key encryption or exhaustive exchanges of information, that are not viable for lightweight wireless devices.[A new generic 3-step protocol for authentication and key agreement in embedded systems]

Protocol should small in code size. You should not to place a separate controller, which deals with communication, into your system. Everything is needed to be inside one small and cheap device. Business requires as low price as possible, because only that it could give you any money.

Embedded networking has constraints that developer should keep in mind while developing a system.

Embedded Network Constraints [A Flexible Approach to Embedded Network Multicast Authentication] Embedded networks usually consist of a number of Electronic Control Units (ECUs). Each ECU performs a set of functions in the system. These ECUs are connected to a network, and communicate using a protocol such as CAN, FlexRay, or Time-Triggered Protocol (TTP). These protocols are among the most capable of those currently in use in wired embedded system networks. Many other protocols are even less capable, but have generally similar requirements and constraints:

- **Multicast Communications** - All messages sent on a distributed embedded network are inherently multicast, because all nodes within the embedded system need to coordinate their actions. Once a sender has transmitted a packet, all other nodes connected to the network receive the message. (In CAN, hardware performs message filtering at the receiver based on content.) Each packet includes the sender's identity, but does not include explicit destination information. The configuration of the network is usually fixed at design time, and changes a little or does not change at all.
- **Resource Limited Nodes** - Processing and storage capabilities of nodes are often limited due to cost considerations at design time. Controllers, that are used usually have no more than 32 kilobytes of RAM and 512 kilobytes of Flash memory. Their operating frequency is no more than 100 MHz. Authentication mechanisms which require large amounts of processing power or storage in RAM may not be feasible.
- **Small Packet Sizes** - Packet sizes are very small in embedded network protocols when compared to those in enterprise networks. The bandwidth is very limited. Network synchronization and packet integrity checks should be added to this. For example data rates are limited to 1 Mbit/sec for CAN and 10 Mbit/sec for TTP and FlexRay. Devices cannot store large packets in memory during processing, as it was mentioned in previous requirement. Authentication should have minimal bandwidth overhead.
- **Tolerance to Packet Loss** - Embedded systems often work in a very noisy environment. Data may corrupt during transmission. Authentication schemes must be tolerant to packet loss.
- **Real-Time Deadlines** - In real-time safety-critical systems, delays are not tolerated. Processes should be completed within specified deadlines. Authentication of nodes must occur within a known period of time. There should not be unspecified delays.

Challenge-Handshake Authentication In this work i decided to use Challenge-Handshake Authentication Protocol [<http://tools.ietf.org/html/rfc1994>].

CHAP is an authentication scheme used by Point to Point Protocol (PPP) servers to validate the identity of remote clients. CHAP periodically verifies the identity of the client by using a three-way handshake. This happens at the time of establishing the initial link (Link control protocol), and may happen again at any time afterwards. The verification is based on a shared secret (such as the client user's password).

1. After the completion of the link establishment phase, the authenticator sends a "challenge" message to the peer.
2. The peer responds with a value calculated using a one-way hash function on the challenge and the secret combined.
3. The authenticator checks the response against its own calculation of the expected hash value. If the values match, the authenticator acknowledges the authentication; otherwise it should terminate the connection.
4. At random intervals the authenticator sends a new challenge to the peer and repeats steps 1 through 3.

The secret is not sent over the link. Although the authentication is only one-way, you can negotiate CHAP in both directions, with the help of the same secret set for mutual authentication.

This protocol is described in the document [<http://tools.ietf.org/html/rfc1994>]. Document specifies main protocol concepts and packet formats.

There are some protocol extensions like MS-CHAP and CHAP is used as a part of other protocols like EAP(EAP MD5-Challenge) and RADIUS (uses CHAP packets). They all use CHAP concepts somehow.

One of the main purposes of this work is to develop a prototype of an embedded service. This system uses JSON [SEE JSON SECTION] object format to encapsulate pieces of information. I will port CHAP packet format to JSON object. It needs to be the same CHAP protocol but it should be placed into JSON. See [CHAP IMPLEMENTATION SECTION] for more details.

Conclusion Information security is a continuing process. There are lots of scientists all over the world, that are trying to invent new approaches how to protect data.

In the Internet-connected future, designers will have to port existing security approaches to embedded control systems. This requires the use of lightweight security protocols.

Embedded control and acquisition devices may be integrated to the main infrastructure of the several organisation. These connections need to be secure enough. Recent decades ago Internet was also a research project, and top computers were like nowadays microcontrollers are. But now it is used in whole world as one of the main communication methods. Even banks are using it for transactions. There are lots of security schemes with different level of protection. I believe that even small 8-bit microcontroller can be securely connected to World Wide Web in the near future.

2.4 Data serialization

2.4.1 JSON

2.4.2 XML

2.4.3 Others

3 System architecture

This section will introduce you a main architecture of the system.

3.1 Introduction

Here will be about coffee machine example in general

3.2 Server architecture

3.3 Client architecture

4 Implementation

Here will be implementation report.

4.1 Implementation of the embedded server

Here will be STM32 server implementation.

One solution is to use closed encrypted proprietary protocol and be calm, but as it was mentioned earlier, it limits the possibility of integration between other embedded systems. In this case all of your devices should support that protocol and your choice of different hardware is limited. Proprietary protocols are often vendor-specific, code is closed, documentation is not free and all it works only with the proprietary devices from the manufacturer.

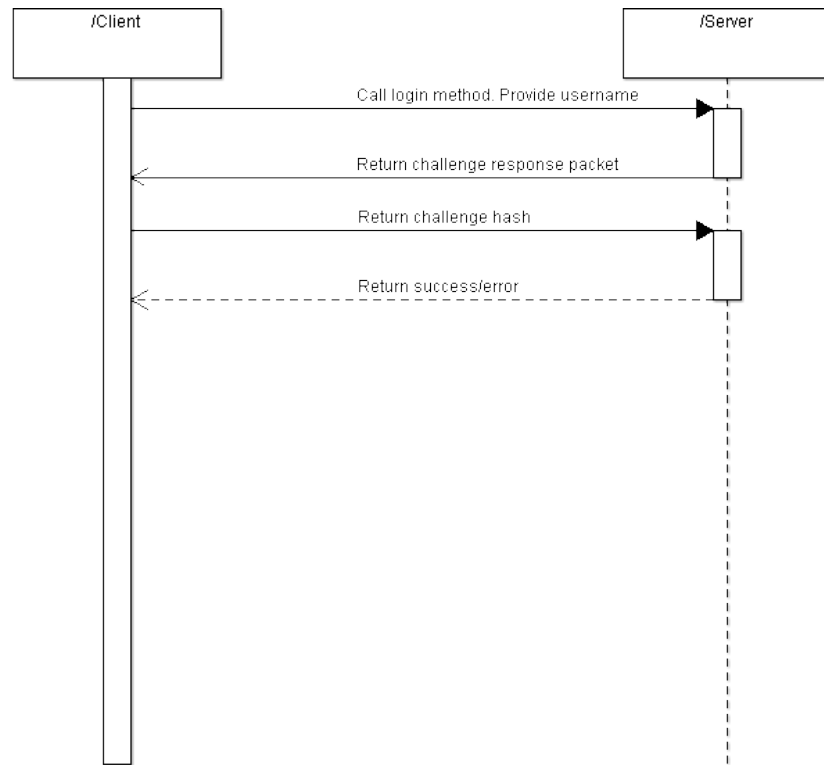


Figure 3: Client authentication process

reversably encrypted form.

4.2 General purpose service library implementation

Here will be general purpose library implementation report.

4.3 Implementation of android client

Here will be android java client implementation report.

Android development Some words about development under Android platform

5 Conclusions

5.1 Future work

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