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MASTER THESIS – Communication Systems Group, Prof. Dr. Burkhard Stiller

Cloud Radio Access Network in LoRa

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Abstract

Das ist die Kurzfassung...

Acknowledgments

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Chapter 1

Introduction and Motivation

Scalability and improvement of Internet of Things (IoT) devices and protocols are important research questions. Low Power Wide Area Networks (LPWANs) technology offers long-range communication with low poser requirements. Battery powered LPWAN devices can run for years. For instance, a node sending 100B once a day lasts for 17 years [1]. LoRa (short for Long Range) is a spread spectrum modulation technique, a wireless radio frequency technology for long range and low power platforms and has become the de facto technology for IoT networks worldwide [2]. LoRaWAN is the open standard backed by the LoRa Alliance. It is a communication protocol and Medium Access Control (MAC) protocol built on the physical LoRa layer. LoRaWAN is designed from the bottom up to optimize LPWANs for battery lifetime, capacity, range, and cost [3]. There are 142 countries with LoRaWAN deployments, 121 network operators, and 76 LoRa Alliance member operators. Swisscom, Amazon, IBM, CISCO are merely a few of the notables LoRa Alliance members [4]. TTN (The Things Network), also a LoRa Alliance member, provides a worldwide LoRaWAN network for and from the community. Anyone with a LoRa gateway can register their gateway on TTN, thereby extending the networks reach. At the time of writing, TTN has 95'208 members, 9'786 gateways, and is present in 147 countries [5]. As LoRaWAN operates in the unlicensed ISM (Industrial, Scientific and Medical) radio bands. Therefore no government license is required to operate LoRa devices and gateways. This allows hobbyist, enthusiasts, and developers to quickly get started and open networks such as TTN to grow rapidly.
In a typical LoRaWAN use case, an IoT device such as a sensor sends data out over the air. Then a LoRa gateway picks the signal up, decodes it, and forwards it over the Internet to the network server which then can send the packet to the application server. If needed, a response message can scheduled on the network server who then chooses the best gateway to send the response back to the IoT device. LoRa gateways carry the full implementation of the LoRa PHY (the physical layer), the LoRaWAN protocol, as well as the packet forwarder. This architecture of the LoRa gateway can be separated and technological stack on the gateway can be reduced by running the signal processing functions not on the gateway itself but in a cloud environment. Such a Cloud Radio Access Network (CRAN) has been previously shown to be beneficial in the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) [6]. The gateway then is left with only minimal functionality it has to support. As the decoding does not take place on the gateway

itself, it does not need do have any LoRa specific hardware e.g the SX1276 transceiver chip found on LoRa devices and gateways. Rather, the gateway is equipped with an antenna, an amplifier as well as digital to analog (DAC) and analog to digital (ADC) converters. On the upstream, the gateway receives LoRa radio signals which it converts into Inphase and Quadrature (I/Q) sample stream with the ADC and simply forwards them to the cloud signal processing unit via the internet. On the downstream the cloud unit streams a LoRa signal as I/Q samples to the gateway which converts it with the DAC to an analog signal and propagates it out over the air. Signals are encoded and decoded on the cloud unit, the Radio Cloud Center (RCC). There are many advantages in such a setup but they come at a cost. First advantage is that the gateway can be kept at a much simpler design resulting in significant manufacturing cost reduction. Also, modifications to the LoRa PHY or LoRaWAN are easier to introduce as the physical layer is implemented in software. Gateways that are once deployed do not need to be physically replaced in case of an upgrade as they are agnostic to the underlying protocol and just convert and transceive (transmit and receive) I/Q samples. Updates to the protocol can be realized with just updating the software implementation. A Low Power Network (LPN) provider saves cost by not having to drive out to the deployed gateways throughout the country to upgrade their versions. The disadvantage is the high throughput of the I/Q samples stream between the gateway and the RCC. Streaming the I/Q samples between gateway and RCC has significantly higher bandwidth requirements than just demodulating the signal on the gateway and forwarding the decoded LoRa packet as it is done in the non cloudified setup. Cloudifying the LoRa gateways also brings the advantages of setting the base for Software Defined Networking (SDN) and Network Function Virutalization (NFV) by centralizing the resources in the RCC that were before distributed on the individual gateways. Goal of this work is setting up a CRAN architecture for LoRa by simplifying the gateways as described above and moving the signal processing out of the gateway into a cloud ready environment i.e., Docker.

1.1 Description of Work

This work first gives a general introduction to LoRa, LoRaWAN and its applications, then dives into more details regarding the LoRa physical layer. Then it gives an overview over existing software implementations of the LoRa PHY. There are two main contributions. First, this work implements a CRAN for LoRa, gives an architectural overview as well as the implementation details. It evaluates the architectural and network related requirements. We developed a simple protocol in raw LoRa, meaning not compliant with the LoRaWAN standard, where a hardware IoT device has a queue of packets to transmit then, depending on wether it requires an acknowledgment, waits for a few seconds for a response or just transmit the next packet in the queue in an interval. If the packet required to be acknowledged but no acknowledgment is received, the same packet will put as first item in the queue. We use this protocol to analyze our CRAN for LoRa architecture.
Second, as the LoRa PHY is closed source, there is no official documentation on how the LoRa PHY is implemented. The existing implementations are all reverse engineering attempts with various degree of success. They all focused first on decoding LoRa signals transmitted by a real LoRa hardware. For the CRAN to work, not only is it necessary

to decode signals but also the encoding of downstream LoRa gateway signals is required. To achieve this we developed a tool that allows the generation of downstream signals in software.

1.2 Thesis Outline

Chapter 2

LoRa and LoRaWAN

LoRa is a modulation technique derived from chirp spread spectrum technology[2]. Originally developed by Cycleo, a french company, LoRa has been acquired by Semtech [7]. LoRa signals spread over multiple frequencies using the whole available bandwidth. This makes the signal more resilient against noise on a disrupting frequency. As LoRa signal are sent over the unlicensed ISM bands, this resilience is an important factor. While LoRa is the modulation technique on the physical layer, LoRaWAN on the other hand is an open communication protocol backed by the Lora Alliance. LoRaWAN specifies packet format, duty cycles, key exchanges and many more things needed for an efficient and cooperative LoRa network. A LoRa network is and LPWAN where battery powered devices can stay operating up to 17 years, making LoRa a popular choice for IoT devices as shown in the example given in the introduction in chapter 1. The TTN network for example is used for cattle tracking, smart irrigation as well as smart parking applications [5].

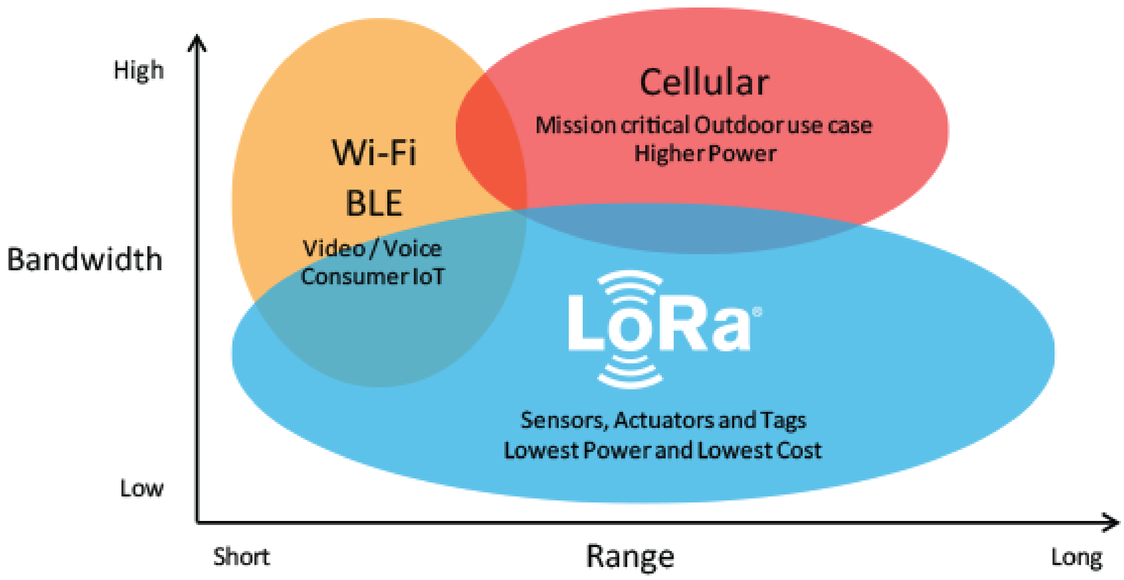

Figure 2.1: LoRa vs other wireless technology[8]

Figure 2.1 shows LoRa compared two other wireless technologies, Wi-Fi and cellular. Both

Wi-Fi and cellular are high in bandwidth with cellular having a longer range than Wi-Fi. They both have a much higher power consumption compared to LoRa. LoRa has lower bandwidth but a high range. In a experiment during a TTN conference LoRa signals from a low orbit satellite were received [9]. On the other hand, as LoRa is designed for long range and low power, only few bytes are transmitted per day while Wi-Fi and cellular are capable of video streaming. In urban areas LoRa has a range of 2-5 km and 15 km in suburban areas [7].
LoRaWAN is not the same all around the world. There are regional parameters that come into play, one is for example the frequency band. In Europe LoRaWAN operates on the in the 863-870MHz and 433MHz ISM band and in North America the 902-928MHz ISM band. Also channel bandwidth and maximum transmission settings are regulated by the government and thus are not the same for all regions [10].

2.1 LoRaWAN architecture

A LoRaWAN network architecture is a star-of-stars topology. The gateways relay the messages between the end-devices and a central network server. Gateways are connected to the network server via IP connections, converting the RF packets to IP packets and vice versa [11]. Network nodes are not associated with a specific gateway, rather messages sent by a node can be received by multiple gateways. Each gateway will then forward the the message to the network server who does the complex things such as filtering redundant packages, security checks, forwarding the messages to the right application server etc. [3]. As network communication is bidirectional, the network server is also responsible for scheduling responses to the end-nodes. There are different classes of end-nodes which will be described in the next section.

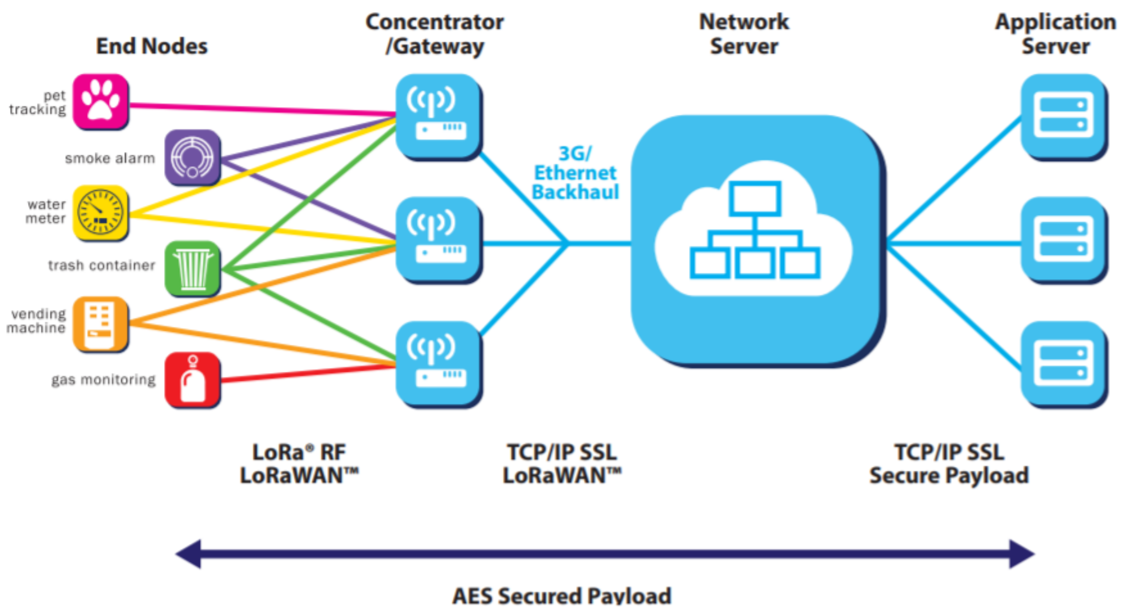

Figure 2.2: LoRaWAN network architecture [3]

As depicted in Figure 2.2, the packets sent by end-devices (on the far left) such as alarms, tracking devices and monitoring devices, can be received by multiple gateways. As the end-nodes are not linked to a particular gateway, the can be moved freely which is an important requirement for assets tracking.
The Figure also shows how security is built into LoRaWAN. The payload is end-to-end encrypted from the end-nodes to the applications server. A unique 128-bit network session key is shared between the end-device and the network server and another 128-bit application session key is shared end-to-end at the application level [11]. With those measures LoRaWAN prevents eavesdropping. Spoofing is prevented by a MIC (Message Integrity Code) in the MAC payload, and replay attacks are prevent by utilizing frame counters [12].

2.2 End-node Classes

There are three classes of end-devices. The following description is adapted from the LoRa Alliance guide [11, 2]:

- Class A, Lowest power, bi-directional end-devices:

  This is the default class, supported by all LoRaWAN devices. It is always the end-node that initiates the communication. After an uplink two downlink windows open for the end-device to receive a response, enabling bi-directional communication. Either the first is used, or the second, but not both receive windows. The end-device can rest in low-power sleep mode, wake up when it needs to send a packet, receive a response in the downlink window, then go back to seep. This is an ALOHA-type of protocol. Class A devices have the lowest power consumption. Downlinks from the server have to wait for an uplink from end-device and cannot be initiated directly.

- Class B, Bi-directional end-devices with deterministic downlink latency:

  Additionally to Class A receive windows, a Class B device opens extra receive windows at scheduled times. This is achieved by time-synchronized beacons from the gateway to the end-device to notify the end-device to open a receive window.

- Class C, Lowest latency, bi-directional end-devices:

  Devices of this class have always open receive windows, except for when they are themselves transmitting. A downlink transmission can be initiated by the network server at any time (assuming the device is not currently transmitting) resulting in no latency. Class C devices however use the most energy. They are more suitable for plugged in devices rather than battery powered devices.

2.3 LoRa signal (uplink)

2.3.1 Chirps

A LoRa signal is a series of so called chirps as LoRa is derived from the Chirp Spread Spectrum modulation (CSS) technique. There are up-chirps and down-chirps. In CSS chirps are deliberately spread across the available bandwidth. Up-chirps go from low frequency to high frequency and down-chirps go from high frequency to low frequency. In Europe the LoRaWAN bandwidth for is 125 kHz. Assuming a center frequency of 868.5 MHz, which is in the european ISM band, a full up-chirp, so called sweep, would go from 868.4375 MHz to 868.5625 MHz.

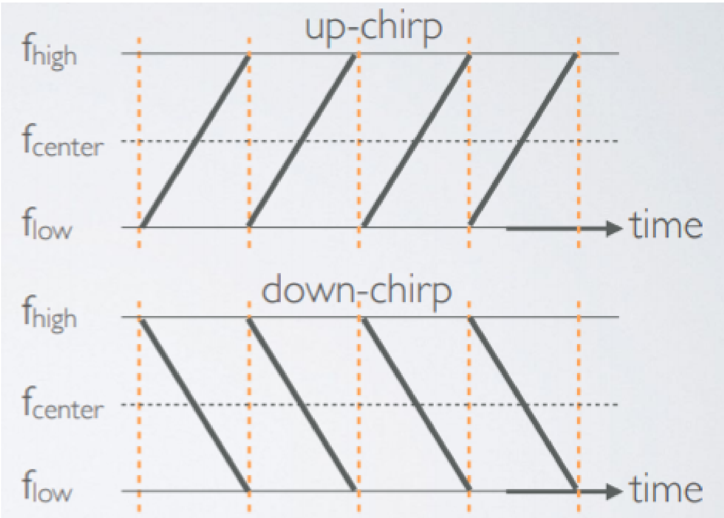

Figure 2.3: Up- and down chirps [13]

Figure 2.3 shows the linear frequency increase resp. decrease over time over the full bandwidth for up-chirps and down-chirps. Data is encoded by frequency jumps in the chirps.

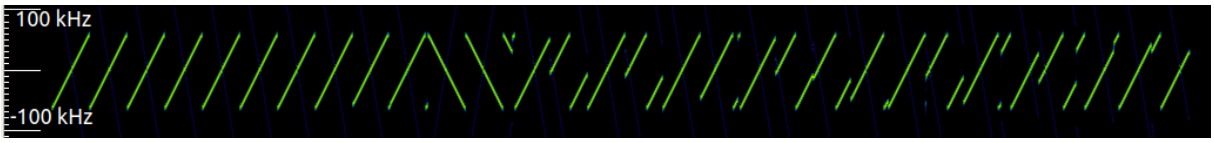

Figure 2.4: Own recording of uplink transmission by arduino equipped with a LoRa shield

The LoRa signal shown in 2.4 carries the message "Goodbye !". This message was sent with a spreading factor (SF) of 9 and coding rate of 4/5. The terms spreading factor and coding rate will be discussed later on.
As one can see, a typical LoRa signal start with a so called preamble, which are the 10 up-chirps at the beginning. Those are followed by two down-chirps, which signify the end of the preamble and the start of the actual payload. In this payload is a header, the actual encoded message followed by a Cyclic Redundancy Check (CRC). The CRC is used for error correction.

2.3.2 Symbol and Spreading Factor

A LoRa signal holds various symbols. A symbol encodes one or more bits of data. The spreading factor determines the number of encoded bits in a symbol. In the shown recording one symbol holds 9 bits of data as the spreading factor of that signal was set to 9. It follows that a symbol has 2^{SF} values. Those values range from 0 to 511 in case of SF 9. A sweep signal of SF 9 thus has 512 chips (no to be confused with chirps) [14]. The chips go linearly from low to high and then wrap around once the maximum frequency is reached.
In Figure 2.5 a fictional symbol with SF 7 is shown. This particular arrangement of chips highlighted in orange would denote the symbol "1011111". Those 7 bits correspond to the decimal value 95.

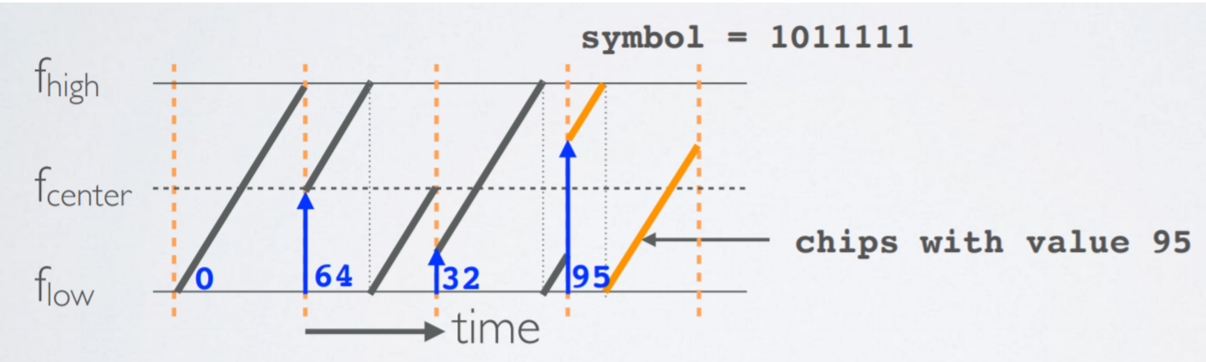

Figure 2.5: Chips and symbols value [14]

In Figure 2.6, a real world example is shown. The same LoRa signal as in Figure 2.4 with SF 9 with the message "Goodbye !" run through modified version of the LoRa decoder by Robyns et al. [15] and then through a python script where we match the samples to the symbols and their values. The last symbols encodes the hex value 142 which corresponds to these 9 bits "101000010". In a SF 9 signal each symbol encodes 9 bits.

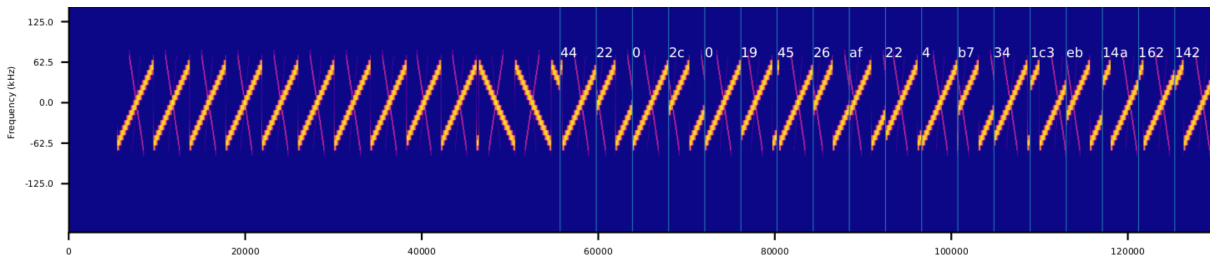

Figure 2.6: Running the signal through our toolchain, matching symbols with samples

2.3.3 Coding Rate

LoRa signals are encoded with a coding rate (CR). The CR denotes the proportion of how many bits carry actual information. The bits that do not carry information are used for Forward Error Correction. The formula for coding rate is $CR = 4/(4 + CR)$ where CR $\in \{1, 2, 3, 4\}$. A CR of 1 is thus the proportion of 4/5 of actual information over bits used for error correction[16, 17]. With FEC, corrupted bits e.g. due to interference can be corrected. With CR of 4, corresponds to $4/8 = 1/2$, half the transmitted bits carry information, the other half is for FEC. The higher the CR (from 1-4) the more bits can get corrupted and corrected by FEC. On the other hand, the higher the CR the more bits need to be transmitted which drains the battery more.

2.3.4 Spreading Factor & Time on Air

The longer the packet, the longer the transmission time. LoRa packets can be shortened by omitting the optional CRC field or sending packets with implicit header mode where the no header is sent and the settings that would have been specified in the header have to be predefined manually on the end device.
Assuming constant packet size and same bandwidth, varying the spreading factor increases resp. decreases the time on air. The higher the SF, the longer the time on air. Higher SF means longer range. The spreading factor goes from 7 to 12. SF 7 has the shortest range, SF 12 the longest. The spreading factor essentially sets the duration of a chirp, a full sweep [18].
The symbol time is defined in the LoRa Design guide by $T_{sym} = \frac{2^{SF}}{BW}$ [16]. It follows as stated above, that the higher the SF the longer the symbol duration. Also, the higher the bandwidth (BW) the shorter the symbol duration. In Europe the BW is 125 kHz, while in North America a BW of 500 kHz is allowed. It also follows that with an increase in SF by 1 the symbol duration is doubled. The bit rate R_b is then defined by $R_b = SF * \frac{[\frac{4}{4*CR}]}{[\frac{2^{SF}}{BW}]}$ with CR being the coding rate for the error correction scheme [19]. It follows from the formula that the higher the coding rate the lower the bit rate as with a higher CR more redundancy is added for the error correction scheme. Highest data rate for $BW = 125\, kHz$ and $CR = 1$ is achieved with SF 7 resulting in a data rate of 5.5 kbits/s and the lowest data rate is achieved with SF 12 resulting in a data rate 0.29 kbits/s.
The spreading factors are orthogonal to each other, meaning signals on different spreading factors do not interfere with each other. This is Code Division Multiple Access (CDMA) where a shared medium i.e. the bandwidth is optimized for multiple access.

Chapter 3

LoRa in SDRs

josh blum matt knight pieter robyns

3.1 C-RAN in LTE

advantages graphics

Chapter 4

C-RAN for LoRa

4.1 Goal

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4.2.1 Sending uplink signals

4.2.2 Sending downlink signals

getting a downlink signal recording from thethingsnetwrok recording from private networks manipualting private gateway offline generation of downlink signal see chapter

4.2.3 Transmission protocol

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4.3.1 BBU

4.3.2 RRH

4.3.3 Network

4.4 Implementation

4.5 Results

Chapter 5

Future work

5.1 Limitations

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Chapter 6

Summary and Conclusions

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Abbreviations

AAA	Authentication, Authorization, and Accounting

Glossary

Authentication

Authorization Authorization is the decision whether an entity is allowed to perform a particular action or not, e.g. whether a user is allowed to attach to a network or not.

Accounting

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Appendix A

Installation Guidelines

Appendix B

Contents of the CD