**aMAZE-RT: Secure Management for OpenWRT**

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| A Project Report Presented to  The Faculty of the College of Engineering |
| San Jose State University In Partial Fulfillment Of the Requirements for the Degree  **Master of Science in Software Engineering** |
| By |
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| December/2020 |

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ABSTRACT

aMAZE-RT: Secure Management for OpenWRT

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A router is a device that helps to interconnect two or more networks, by forwarding data packets between them [1]. Home and Small office networks typically connect to the internet via consumer-level Wi-Fi routers, which provide wireless access points to the devices at home and route packets to the modem.

Typical consumer routers have locked firmware which restricts the functionality to whatever the device manufacturer decides to include. Open Source software stack like OpenWRT (Open Wireless Router) can be used to enhance the functionality and device security of consumer and custom Wi-Fi routers. Management of OpenWRT based devices is done using a browser or command-line interface. While this may work for the tech-savvy, a large majority of users may not be comfortable managing their devices this way. Some consumer-level devices have moved towards mobile app-based management, but OpenWRT lacks a mobile app-based router management functionality.

In this project, we plan to develop an end-to-end secure software to manage routers using a mobile application, with a customized version of OpenWRT, a mobile app as the front end, and an optional cloud-based management system for communication. The app provides features like monitoring and managing connection attempts with the notification on the mobile app via the cloud. Mobile App shall manage router connection attempts as an additional authentication factor on top of the Wi-Fi user authentication, enabling Multi-Factor Authentication. We also plan to port the major features of the LuCI web-based management tool for OpenWRT to the App, such as Access Control, package management, real-time monitoring, etc.

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# Project Overview

## Introduction

* + 1. A router is a device that interconnects two or more networks, by forwarding data packets between them [1]. Routers can interconnect multiple public networks on the internet, such as the ones used in the internet backbone and interconnections between internet service providers [1]. Internet access in small offices and home environments typically is done via a broadband modem that connects to the public internet via the Internet Service provider. On the internal network, multiple devices may share the internet connection by using a wireless router, which interconnects the local network to the public network via the broadband modem. Figure 1 - Typical Configuration of Home Network shows how a typical home network connects to the internet using a wireless router.
  1. **Diagram

     Description automatically generated**

Figure Typical Configuration of Home Network

The consumer router market comes with a plethora of brands and models supporting varying hardware and software features. They often restrict the user with locked firmware limiting the features and functionality to a subset of possible features, as conceived by the device manufacturer. Like in the case of many commercial software products, Open Source software stacks provide an alternate option to enhance the functionality and security of consumer routers. OpenWRT is such an Open Source Linux based Wireless router firmware. OpenWRT supports a wide range of hardware. There are many commercial products available based on OpenWRT. Customers can add packages to enhance the functionality of the router. OpenWRT devices provide web-based administration that provides very advanced configuration and management functionality. This would not work for a large majority of novice users who would find it hard and technically demanding to manage their devices this way. There are only a handful of consumer-oriented devices that have ventured towards mobile application-based device management. This is one area that OpenWRT falls behind and even a basic mobile application-based router management functionality will benefit all the consumers in a big way. The trend towards using mobile apps for everything has made routers with mobile App based management more appealing for a large group of users, who would otherwise not even bother to configure the router with the web-based management tools [2].

## Proposed Areas of Study and Academic Contribution

Need to add relevant information here.

## Current State of the Art

OpenWRT firmware is based on the Linux operating system. The system provides a shell (ash shell) for running commands for making configuration changes. The fact that this is based on Linux makes it easy for extending the functionality, unlike other firmware options. OpenWRT provides a standardized way of implementing enhancements, called packages [3]. Each package is analogous to an application that can be installed on the device, extending its functionality. OpenWRT community also develops and maintains a list of around 3500 packages [4]. A Web-based management interface is provided which can be installed as a package on the device [2]. like art is currently supported in a wide range of router hardware. OpenWRT provides LuCI Web-based user interface for router administration and monitoring [5]. The UI is a bit complex to manage and operate for most of the home consumer router users. The following figures give a glimpse of the complex UI from OpenWRT

* 1. Graphical user interface

     Description automatically generated

Figure LuCL Web App UI – 1

* 1. A picture containing graphical user interface

     Description automatically generated

Figure LuCL Web App UI – 2

* 1. Graphical user interface, application

     Description automatically generated

Figure LuCL Web App UI - 3

For the not so tech-savvy end-user, management via a Web-based UI can be an uninteresting task when it involves remembering the IP Address, requiring login every time an administration or monitoring task needs to be done. This also has a negative impact on the security aspect of the router, since the users are mostly unknown about who is connected to their network, or what apps are using most data. There exist some hobby projects that provide basic mobile app functionality, but they are limited to basic management functions, and do not have any cloud support.

### State-of-the-Art Summary

There is no doubt that OpenWRT is an excellent open-source alternative for router firmware, providing one of the richest sets of management and security tools. However, having only a command line or web-based management and monitoring interface is a deterrent for most consumers in the era of mobile apps.

## Project Justification

OpenWRT is a feature-rich open-source wireless router firmware. It has a rich set of features and together with the active community support and contribution makes it a leader in its arena. The OpenWRT software stack is well adopted by a wide range of hardware vendors. Despite the rich feature set and much-desired hardware adoption, there is one much-desired improvement to the software stack, a mobile management app. When it comes to management and monitoring interfaces, the lack of a mobile app for continuous monitoring and configuration management is the Achilles heel of the system. No matter how advanced the available web interface features are, their usage mandates a browser and logging in every time something needs to be checked. Mobile app-based configuration and monitoring can solve this drawback by providing a simple user-friendly management and monitoring interface. In this era of mobile apps for everything, the availability of an average mobile application-based interface would cater to most of the internet users of the world. OpenWRT lacks in this area with no serious mobile application-based management and monitoring solutions being developed.

The project aims to improve the user adaptability and adoption rate of the OpenWRT stack. This will be done by adding a mobile application-based interface to manage and monitor the OpenWRT router. Cloud-based support for real-time monitoring and management of the router will be added to further enhance the adoption rate and user-friendliness of the software stack. The result will be an OpenWRT based software stack that supports mobile app-based management and monitoring of OpenWRT routers.

# Project Architecture

## Introduction

Include introductory text plus a diagram.

Diagram

Description automatically generated

Figure Project Architecture

TODO: Redo the Diagram as vector

## Architecture Subsystems

The entire project is divided into 3 major architectural subsystems as below.

1. The Mobile App used to provide the front-end functionality
2. The software that runs on the OpenWRT providing status updates and handling configuration changes
3. The business logic to manage and handle communication between OpenWRT device and Mobile App, which runs on Google Cloud Platform
4. The Secure Shared Database which keeps track of the device settings and provides real-time notifications to Mobile App about configuration changes

# Technology Descriptions

Assume you audience is a skilled computer scientist that has some familiarity with technologies taught in the client/server program. The topics below are for a typical MS Software Engineering project. Adjust the topics in this chapter to meet the needs of your project.

## Client Technologies

### Mobile App

Mobile application is an Android App on the mobile device running Android OS level 29 or later. This is a front-end application to configure and control the OpenWRT device. The functionalities include device registration, device configuration, device status update, notification handling, device removal.

#### Android SDK

Android SDK is a comprehensive set of development tools for Android app development. The tools include libraries, debugger, QEMU based handset emulator, tutorials, sample codes and documentation. Android application is packaged in “.apk” format. The apk package contains Dalvik executables, resource files etc. Dalvik executables are compiled byte codes. The application is stored in /data/app directory on Android OS and can be accessible only to root user for security.

#### JSch

JSch is a Java implementation of SSH2 based on JavaTM Cryptography Extension (JCE). This library allows to connect to sshd server, port forwarding, secure terminal emulation, secure file transfer etc. SSH2 supports secure file transfer, secure remote login, and secure TCP/IP and X11 forwarding. It automatically authenticates, encrypts, and compress transmitted data.

#### GSon

Google GSon library serializes and de-serializes Java objects to JSON and back. The library provides simple methods to convert JSON to Java object and vice-versa. The library is highly customizable and can take complex java objects. GSon can also work on arbitrary Java objects with no source code available

## AmazeRT Agent

AmazeRT Agent is part of the AmazeRT software that runs on the OpenWRT router device. This is installed during the initial setup and will continue to run in the background, handling communication with the Cloud Backend.

### Python with Websockets

Since OpenWRT Stack can run on a variety of hardware architectures, keeping the AmazeRT Agent independent of the underlying CPU architecture was required. To handle this, we chose to implement it using Python programming language. The AmazeRT Agent software's primary purpose is to handle the communication with the Cloud backend and process the requests forwarded to it from the Mobile App Client. This required a persistent communication channel to talk to the Cloud backend. For communicating with the Cloud Backend, websockets library was chosen since it provided a good infrastructure to handle custom communication protocols on top of the secure TLS layer.

Python also has extensive set of libraries that helps with rapid prototyping of the software, letting us focus on the actual functionality, rather than spending effort on the Lower-level libraries and utility functions. Though OpenWRT SDK provides more low-level libraries and frameworks for developing native applications for OpenWRT based devices, handling different CPU architectures required a lot more effort from developer's side. For the purpose of prototyping, we did not need such low level access to the OpenWRT stack. Due to these reasons, we chose not to use the OpenWRT SDK for the prototyping.

### UUID

Every device that is managed by the AmazeRT system will need to be uniquely identified. A UUID was chosen as an identifier for the device. UUID is a 128-bit number, that can be generated to be uniquely without a central database of all generated Ids [6]. AmazerRT agent also uses UUID to generate a secret password that is shared between the device and mobile app, for securing and validating sensitive data sent across them.

## Middle-Tier Technologies

WebSocket

[…]

Cloud

App Engine

Cloud functions

Figure Cloud Architecture

### App Engine

App Engine is an platform as service infrastructure provided by Google to host an application with out worrying about instance management, scaling, resource allocation etc. It is a Linux container hosted in google public cloud. In this project App Engine instance is used as middle tire facilitating the communication between the Amaze RT device and the mobile application. App Engine takes care of authentication and authorization between Amaze RT device and Firebase Database.

For the communication between WRT device and mobile App an AppEngine (a cloud linux container instance) instance with public websockets is used. WRT devices can connect to this well-known websocket urls to asynchronously talk to the app. This architecture gives the flexibility that, even if the mobile app is not running at that time the WRT device can establish a connection to the websocket and push its message.

### Cloud Function

Cloud functions are serverless computing infrastructures which can be used to invoke a function for a specific event or a trigger. It is used to publish database modifications to App Engine websockets which in turn push the message to corresponding WRT device.

### Websockets with TLS for security for device to App Engine communication

## Data-Tier Technologies

### Secure Data Storage

Mobile App will utilize local device data storage for device specific information.

### FireBase RealTime Database

Firebase Realtime Database used for openWrt router to Mobile App communication including router settings and status notification. Firebase RealTime Database is used to implement the cloud-based device state and event management across managed openWrt devices and their managing applications. The Firebase infrastructure provides User authentication and authorization for appropriate access control. It also provides event trigger and registration mechanisms to help implement the business logic.

### File Encryption for App data storage

EncryptedFile class that is part of the androidx.security.crypto package can create and read encrypted files. The encryption scheme supported by the class is AES256\_GCM\_HKDF\_4KB. MasterKey class references a key that is stored in Android Keystore. The recommended master key size is 256 bytes. The key encryption scheme used by MasterKey class is AES256\_GCM\_SPEC. EncryptedFile class uses the MasterKey class derived Key to encrypt and decrypt the files.

# Project Design

## Mobile App

### App Login UI

The launching page of Mobile App as presented in figure xyz will direct to federated login using Firebase Authentication UI. There is no sign-up feature as the app is Android based and all users will have Google account for login. The federated login screen UI is presented is figure xvz. The user needs to provide the Google username and password only the first time. The user gets navigated to Devices screen only on successful login.

Figure ui1

Figure ui2

### Device Registration UI

Successful login will launch the Device list screen. This screen will list all the registered OpenWrt devices as presented in figure xyz. First time use of the app will not have any device listing. The fab button (with plus sign) on the Device list screen will navigate to Add device screen as presented in figure xyz. The user needs to provide the device name which the OpenWrt device needs to be remembered. App will do an input check if a device with same name is already registered. It will proceed only with a new valid device name. User needs to provide admin username and password of the device to be registered.

Add button will start the registration process. A circular progress bar will be displayed along with the text running display of the registration sequence as presented in figure xyz. Figure xyz depicts the device registration sequence from Mobile app. The device registration sequence is as follows.

1. ssh to OpenWrt device using JSch library and execute commands to install secure ftp daemon and start the daemon.

2. Securely copy the device package that is bundled in Mobile app to device using SFTP.

3. ssh to OpenWrt device, untar the device package and execute install script on the device.

4. Securely copy the device info json file from OpenWrt device to Mobile.

5. Encrypt the device registration json with Android MasterKey and save in App data space.

6. Register the OpenWrt device on Cloud using Firebase database.

7. ssh to OpenWrt device and start the device software.

After the device registration is done, the Done button will appear on the same screen as presented in Figure xvz. Done button will take the user back to Device list screen. This screen lists the currently added device along with all OpenWrt devices registered before.

### Device Settings UI

Mobile App provides support for managed openWrt device settings configuration. This acts as a user’s primary access point to control the features provided and exposed by the openWrt device. The settings screen follows the device registration control flow by an authenticated user for App registration. At this point in the control flow, the authenticated user’s Unique Identifier and the registered device’s unique identifier are generated and available. These Unique Identifiers that are encrypted using the device symmetric key are decrypted and stored in process memory. The settings UI is designed using the MVC design paradigm. A combination of recyclerView, viewModel and adaptor is used to capture and display the device settings data using a livedata model with observer.

1. Settings fetch

The settings data is fetched from the Firebase Database that holds the current device settings data and acts as a communication proxy between the openWrt device and the Mobile App. A Firebase Livedata will be fetched using the built-in listener class. The listener class links to the firebase url and settings path referred to by the listener object. This allows for instant updates to be delivered from the firebase Realtime database to the registered mobile application. The fetched data from the Firebase Realtime database will always be the latest value for each setting updated from the corresponding device.

1. Settings push

The settings data reconfiguration is facilitated through a child UI screen. Each setting update happens over a child screen that supports single setting reconfiguration. User is presented with all possible options for the current setting that is selected for update. Once user confirms update of the setting, the same is updated using the setting path reference and of the Firebase Realtime database url.

### Device Status UI

Mobile App provides support for user to view current device status. The status UI screen is designed using the MVC design paradigm. A combination of recyclerView, viewModel and adaptor is used to capture and display the device status data using a livedata model implemented with an observer. Firebase Realtime database proxy provides the live status data updates over a dedicated status path for each device. Status UI captures the details of devices that are connected to the openWrt device including the burned in MAC address. openWrt device status that captures the current running status of the device is also captured here along with device bootup time.

### User Profile UI

Mobile App has a Toolbar on all screens once logged in. The Toolbar has user profile icon on the right corner as presented in Figure xyz. Google profile photo is displayed on the user profile icon. User click on user profile icon will take to User profile screen as presented in Figure xyz. This screen provides option to logout from the current user login. Logout will take the App back to the launch screen to login.

## AmazeRT Agent

AmazeRT agent is the part of the AmazeRT software stack that runs on the OpenWRT router. It starts as soon as the router boots, and keeps running until shutdown. The primary purpose of device software is to handle all the communication between the device and the Cloud backend service. It periodically sends the device’s settings and current status to the Cloud backend and also handle different requests originating from the Mobile App, forwarded by the Cloud backend. The agent is designed to run on any device that support OpenWRT software stack.

### Registration and Installation

The AmazeRT agent software is designed to be installed on the OpenWRT router by any user who has administrative access to the device. Since the software is designed to be independent of the the OpenWRT SDK and associated ecosystem, we package this along with the mobile app used as a client for the entire software stack. The basic sequence of device setup includes copying the installation package to the router, running the install scripts to install and generate device id and keys, and then restart the router .

There are two installation scripts provided in the package. The first one, *“install.sh”* is a shell script which is used for ensuring all the required dependencies are met. It uses the OpenWRT package management system called opkg to install all the required packages, including python, websockets, cryptography libraries. Once all the dependencies are installed, the AmazeRT agent files are copied to the right locations. It also setup the router to start the AmazeRT Agent on boot, making sure the communication with Cloud backend is functional across reboots.

### Cloud Registration

When the AmazeRT agent starts, if it is able to communicate with the Cloud backend, we assume that the router is in a consistent state. Any data in the cloud about the settings may be different from what is on the router. There is no guarantee that these settings are in a consistent state. To prevent such conflicts from corrupting the device state later, we will need to overwrite all that settings in cloud to the one from the router. Once the agent starts, it prepares an initial registration packet which contains the all the supported settings and current status. This packet is then filled with the device identification data, and all the settings are encrypted and signed for security, and then sent to the Cloud backend. Once this completes, the state in router and the Cloud backend are in sync. The mobile app will be able to pull the data from the cloud database. The registration packet is only sent once during the boot, when the agent starts. If the agent is restarted for any reason, a registration packet is resent with the updated data. This is to handle the case where one or more setting might have changed thorough other management interfaces like LUCI or command lines.

### Heartbeats and Status Updates

The registration packet sent initially will have a complete set of settings and status from the router. The settings may change due to updates triggered from other interfaces like LUCI or even command line settings. The router status also may change due to Wifi clients connecting or disconnecting from the device. The AmazeRT agent will keep sending such updates to the cloud backend at a fixed interval so that the mobile app UI can be updated with the right data. These packets are referred to as “Heartbeat packets”. The structure of the heartbeat packet is similar to the registration packet, except that the settings are filtered to remove those that did not change from last time it was sent to the cloud backend. Note that the setting values are encrypted and signed, each time with a different nonce also added, so even if the setting value did not change, sending the setting to cloud will trigger a change in the database. This filtering reduces the number of setting updates that need to be handled from the mobile app side too.

### Device Configuration Management

Mobile app may change the value for any setting that is supported by AmazeRT, by updating it in the cloud database. The cloud backend will process the change in value for the the setting and generate a setting request packet to be sent to the router. The packet shall have the device identification data and sent to the router. AmazeRT agent will then process this request and extract all the settings embedded in the packet and apply those settings locally. Once the settings are updated, the heartbeat packet will take care of sending the update back to the cloud. If for any reason the setting is rejected, the next heartbeat is forced to sent a full update, so that the cloud database is restored to a valid state. This change will also cause the Mobile app to update the device settings on the UI.

In addition to handling setting changes, AmazeRT agent supports a “command” packet to execute any generic command on the router. This helps implementing support for device reboot, uninstallation of AmazeRT agent, or any other special updates using this framework.

### Failure Handling

The AmazeRT software stack relies on the AmazeRT agent running on the router, handling all the communication with cloud backend. The AmazeRT agent also requires a persistent connection to the cloud to handle communication. However this cannot be guaranteed due to the possibility of network disruptions etc. To handle these kind of issues, AmazerRT agent is run with a lightweight wrapper called “runner” which keeps restarting the agent if the main application stops for some reason. The main application is then written to gracefully exit if there is any communication failure with the cloud, or any unexpected error during its execution. The runner then restarts the agent and re-establish connection with the cloud backend.

## Business Logic

### Websocket

### AppEngine

### Cloud function

## Secure Data Storage

### Shared Configuration Database

Firebase Realtime Database used for openWrt router to Mobile App communication including router settings and status notification. Firebase Realtime database is used as a proxy for real time data update between the openWrt device and the Mobile App. The real time notification and registration capabilities provided by this Google service helps the Mobile App and the openWrt device to communicate through an effective and secure channel.

Data Access Control

Firebase Realtime database rules have been used to achieve data access control for the device data at rest. Write and read access to the data stored and synced in the database is restricted to the authenticated user using the auth rule option. Firebase Authentication feature has been used as the authentication method for user verification and later extended in data access control. User authorizing based on their Firebase authenticated identity is used to ensure and restrict read/write access of device data.

### Device Registration data on Mobile app

Mobile device local storage will be used as secure store for persistence and retrieval of openWrt device registration and authenticated user details.

# Project Implementation

## Mobile App

### App Login UI

### Device Registration UI

### Device Settings UI

This component is responsible for device settings management, allowing the user to view and update openWrt device settings. The Mobile App user authenticated using Firebase authentication APIs can choose to navigate to this UI component. Settings specific to this user and the selected device are displayed with options to edit the same. FirebaseQueryLiveData object is initialized with the Firebase Realtime database settings URL for the mapped user’s device.

1. FirebaseQueryLiveData class

This class is used to add event listener for Firebase Realtime database data change events. This class is derived from the LiveData Data holder class to allow for observing the changes in Database data snapshot. This class is designed and implemented in a generic fashion to instantiate and query device settings or device status database paths.

The instantiated object of this class feeds into the DeviceSetting and Device Status ViewModel class instances.

### Device Status UI

This UI component is responsible for fetching and interpreting the managed openWrt device status. The Mobile App user authenticated using Firebase authentication APIs can choose to navigate to this UI component. Settings specific to this user and the selected device are displayed with options to edit the same. FirebaseQueryLiveData object is initialized with the Firebase Realtime database status URL for the mapped user’s device.

## OpenWRT device software

### Registration and Installation

### Heartbeats

### Status Updates

### Device Configuration Management

### Failure Handling

## Business Logic

### Websocket

### AppEngine

### Cloud functions

## Secure Data Storage

### Shared Configuration Database

### Device Registration data on Mobile app

## Hardware platform

Raspberry Pi 4 was chosen as the HW platform for implementing the router side of software for ease of debugging and availability of enough RAM for running debug tools as needed. For the Android App side, a simulator running Pixel 2 was chosen as the base hardware for prototype testing.

# Testing and Verification

Describe your test strategy, process, and results for verifying the functionality of your project.

## Testing Process

### Mobile App

1. Database rules

Firebase Realtime database rules are used for data access control. The derived rules were tested using a test UI screen with the capability to fetch and derive database URLs based on the passed in values to verify the access controls in place. Database rules were specifically tested for the read and write controls added. Automated tests for this Firebase Realtime database module are being worked upon now.

### OpenWRT Device Software

### Business Logic

### Database testing

## Test results

# Performance and Benchmarks

Describe any performance and benchmarking criteria you used for your project. In addition, describe any benchmarking results you observed in your project.

## Scalability

## Throughput

## Reliability

## Feature Parity

# Deployment, Operations, Maintenance

## Business Logic

### Cloud Functions

Cloud function is deployed in google cloud. When the cloud function is upgraded with new features google cloud updates it reliably without down time.

### App Engine

App Engine is deployed in google cloud as a compute instance. It provides a public IP and a persistent websockets based connection to the managed devices.

## Android App and Device software

Deployed on mobile per device, used for managing the device.

### Android App Stores

### Packaging device software

## Secure Database operations

### Firebase Realtime Database

Firebase RealTime database is used for the AmazeRT device to Mobile App communication.

### Local App database

### Device data storage

## Github repository

Contains all project artifacts.

# Summary, Conclusions, and Recommendations

## Summary

TODO: Reformat the content

Our original design was to use a Custom Linux server running on AWS for the Business logic processing. This changed to use a Google App Engine, Firebase and Cloud functions

With the updated design we could avoid the requirement of a public IP Address and an open port for listening for control requests from the server

The original scope for this project was too big to be completed within the timeframe we had, but we were able to trim down the set of features supported and make the end to end flow working. A framework was implemented to add new settings support with minimal change from the Device software. The UI would require more changes but can be redesigned to make it more data driven.

## Conclusions

1.Achieved all the revised project goals and implemented some of the stretch goals as well.

## Recommendations for Further Research

TODO: Reformat the content

Enhancement of this infrastructure to support device management for Edge computing devices, using Mobile app and the framework provided by the AmazeRT cloud and device management modules

* Extend with IOS application support with SwiftUI for User interface development
* Moving from Firebase to Firestore for the database
* Moving to Android Jetpack compose to design modern scalable UI.
* Redesigning the Android app for generating configuration and status screens using a data driven mechanism so that new features can be added with minimal efforts.
* Integrating this entire software suite with the open source OpenWRT codebase and making this a default install option for all OpenWRT devices.

# Glossary

|  |  |
| --- | --- |
| **Acronym** | **Description** |
| API | Application Programming Interface |
| JSON | JavaScript Object Notation. JSON is a lightweight data-interchange format. It is easy for humans to read and write as well as for machines to parse and generate. |
| XML | Extensible Markup Language. |

Table Glossary

# References

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# Appendices