Title: Digital CBT-I System Design

Course: Internet Of Things

Assignment: Design and Prototype of a Digital CBT-I Support System

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Requirements and Functionality

Objectives

For this proposal, our goals are to **automate and enhance the standard CBT-I Protocol,** by guiding patients through intake, education, stimulus control, sleep restrictions, sleep hygiene, relaxation, and cognitive restructuring. For this, we also aim to collect both objective and subjective data, using wearables and self-reports.

With this approach, we also have the objective of **maximizing patient engagement and adherence**, by reducing friction in data entry and using reminders, gamification and instant feedback.

Finally, we aim to enable clinician monitoring and intervention, since therapists should be able to view the patient's progress, sleep metrics, questionnaire results and adherence and alerts are provided if a patient's metrics cross a risk threshold.

Stakeholders and user Personas

Adult Patient

Varies in tech knowledge, may have limited patience for tedious diary entry. He needs clear, step-by-step guidance and real-time feedback for sleep habits. He is motivated by improved sleep but may struggle with habit formation.

> Beatriz, 24 years old, works full-time and studies computer science, usually is stressed with her heavy routine and, since she is getting very overwhelmed with her habits, she aims to look for a psychiatrist to help her with sleep tracking and habits. For this, she is willing to follow the doctor's recommendations and wants to visualize the data collected.

CBT-I Therapist

Is a licensed psychiatrist/psychologist specializing in insomnia. He needs a dashboard to monitor multiple patients, review sleep diaries, adjust therapy parameters anda send personalized recommendations.

> Carlos, 32 years old, is a psychiatrist in the early stages of his career and recently trained in CBT-I methodology. He is enthusiastic about using digital tools to enhance therapy outcomes and wants intuitive interfaces that allow him to quickly interpret patient data and deliver insights. Carlos values clinical efficiency, security, and clear visualizations to guide his decision-making.

System Administrator

Manages cloud infrastructure, user accounts, data security, and ensures HIPAA/GDPR compliance.

> Juliana, 40 years old, is an experienced system administrator working in a hospital IT department. She is highly focused on data protection, uptime, and regulatory compliance. Renata prefers automation for tasks like access control and auditing, and she needs robust logs and alerts for any unusual behavior. While not involved in patient care, she plays a critical role in maintaining trust and ensuring that all digital health tools function securely and reliably.

Functional Requirements

Data intake and baseline collection

To understand a patient's habits, a questionnaire is going to be used in the App to collect demographics, insomnia history, and comorbidities of the user. The software will have a Sleep Diary, so the patient can answer before-sleep and after-wake questions that the wearables couldn't collect.

Wearable and IoT Data Capture

The wearables used in this system can collect various sleep metrics, including Total Sleep Time (TST), Sleep Onset Latency (SOL), Wake After Sleep Onset (WASO), Sleep Efficiency (SE), and the number of awakenings.

In addition, these devices offer environmental monitoring by tracking factors such as ambient light (lux), noise levels (dB), and bedroom temperature and humidity.

Finally, the wearables can capture physiological markers, such as heart rate variability (HRV) as an indicator of stress or arousal, and actigraphy to assess rest and activity patterns.

CBT-I Protocol Modules

To support patient education, the system will include interactive tutorials covering topics such as Sleep Drive, Circadian Rhythm, and the 3P Model (Predisposing, Precipitating, Perpetuating factors).

One of the goals is to assist with Stimulus Control by providing tailored instructions for the patient's routine, including guidance on getting out of bed after lying supine for 20 minutes without movement or Heart Rate (HR) indications of sleep.

For Sleep Restriction Therapy, we will calculate a baseline average of Total Sleep Time (TST) to establish a prescribed Time in Bed (PTIB), creating a sleep window. The system will automatically generate a bedtime and wake time schedule and deliver push notifications to reinforce adherence.

Additionally, we will implement a weekly titration protocol: if Sleep Efficiency (SE) is below 85%, the PTIB will be reduced by 15 minutes; if SE is between 85% and 90%, PTIB will remain unchanged; and if SE exceeds 90%, PTIB will be increased by 15 minutes.

To support the Sleep Hygiene and Relaxation module, we will offer checklists, practical tips, and embedded guided audio exercises, including Diaphragmatic Breathing, Progressive Muscle Relaxation, and Imagery techniques.

For the Cognitive Therapy (CT) component, users will engage with interactive “Thought Record” templates that prompt them to log maladaptive beliefs (e.g., “I need 8 hours of sleep”) and guide them through cognitive restructuring. Additionally, educational “Myth vs. Fact” quizzes will be included to reinforce adaptive beliefs.

Finally, for Relapse Prevention, we will provide a graphical “Relapse Cycle” visualization that allows users to identify high-risk situations and select coping strategies. Periodic “check-in” surveys will also be delivered following the completion of the main protocol to monitor long-term progress.

Notifications and Reminders

To support adherence and engagement, the system will include Notifications and Reminders across several therapy components. Users will receive Sleep Diary alerts, with evening reminders to complete the pre-sleep portion and morning prompts for the post-wake entries.

Therapy Task reminders will be sent to guide the user through scheduled activities such as Stimulus Control practices, Relaxation Audio sessions, and the Weekly Titration check-in.

To enhance motivation, gamification elements will be included, users can earn badges for milestones such as completing the sleep diary for five consecutive days, achieving the target Sleep Efficiency (SE), or completing cognitive restructuring worksheets.

Clinician Dashboard

On the Clinician Dashboard, healthcare providers will have access to a comprehensive overview of each patient’s progress. A Patient List with visual indicators (green/yellow/red) will display key metrics such as current SE, adherence percentage, and Insomnia Severity Index (ISI) scores.

The Detailed Patient View will include time-series charts tracking Total Sleep Time (TST), SE, Sleep Onset Latency (SOL), and Wake After Sleep Onset (WASO), as well as access to sleep diary entries and self-reported sleep quality. Questionnaire results, including the ISI and Dysfunctional Beliefs and Attitudes about Sleep (DABS), will also be available.

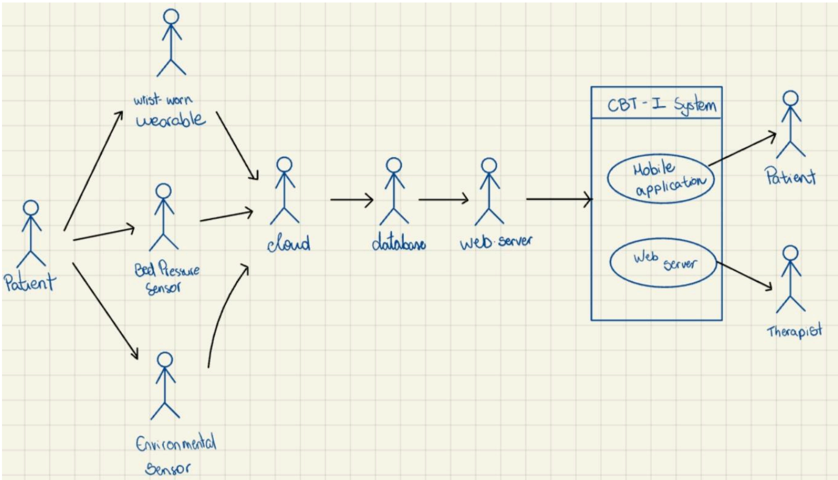
Clinicians will have the ability to adjust treatment by overriding automated titration logic, sending personalized messages, or scheduling telehealth sessions.

A secure, HIPAA-compliant chat feature will facilitate direct communication with patients for support, guidance, or encouragement.

Non-Functional Requirements

The system will meet key Non-Functional Requirements to ensure safety, performance, and user accessibility. In terms of **Security and Privacy**, it will comply with HIPAA and GDPR standards, incorporating end-to-end encryption, role-based access controls, and audit logs to safeguard sensitive data. **Reliability and Availability** will be ensured through a server uptime guarantee, with offline functionality to support basic journaling and wearable synchronization when internet access is unavailable. **Scalability** is addressed through a microservices architecture capable of supporting hundreds of concurrent users via load balancing. The application will prioritize **Usability**, featuring an intuitive user interface with large fonts, simplified language, and a high-contrast color scheme optimized for night mode. **Accessibility** considerations include screen reader support, adjustable font sizes, and audio-based delivery of Cognitive Therapy (CT) questions to accommodate users with low literacy. Finally, **Interoperability** will be achieved through the use of standard Bluetooth Low Energy (BLE) GATT services for wearable data exchange and FHIR APIs to enable potential integration with Electronic Health Records (EHRs).

System Overview (UML Component Diagram Description)



Hardware and Communication Protocols

Component	Functionality	Example Device/Spec	Communication Protocol
Wrist-worn Actigraph	Movement (accelerometer), Heart Rate/HRV	Commercial actigraph (e.g., ActiGraph wGT3X+, Polar H10 strap)	BLE (GATT "Body Sensor" Profile)
Bed Pressure Sensor	Presence detection, Posture changes	Under-mattress piezoelectric sensor (e.g., Withings Sleep Mat)	WiFi (via home gateway)

Environmental Sensor Node	Ambient light (lux), noise (dB), temperature, humidity	Multi-sensor IoT kit (e.g., Particle Argon + BME280 + microphone + light sensor)	WiFi or BLE to smartphone/local gateway
Smartphone (Patient's App)	Mobile gateway, notifications, user input	Android/iOS device	BLE for wearables; HTTPS to cloud
Local Gateway (Optional)	Bridge for non-BLE sensors, MQTT broker	Raspberry Pi 4 with ZigBee/BLE dongles	BLE, ZigBee, MQTT to Cloud

Table1. Wearable and IoT Selection for Digital CBTI System

As seen in Table 1, we can use an Actigraph that communicates with the smartphone using the standard GATT Sleep Profile (Generic Attribute Profile (GATT) is a Bluetooth Low Energy (BLE) profile that defines how data is structured and exchanged between two devices. It provides the framework for creating and using profiles, including those focused on sleep tracking), with custom service UUIDs if necessary. Data packets are transmitted as epoch summaries (30-second or 60-second intervals) containing movement counts and heart rate information.

If the environmental sensor is within BLE range, the smartphone can directly poll it every 5 minutes to retrieve measurements of light level (lux), noise level (dB), temperature (°C), and humidity (%). If BLE is not feasible, the sensors connect via ZigBee (2.4 GHz) to a local gateway (e.g., a Raspberry Pi), which then aggregates the data and forwards it to the cloud over WiFi or Ethernet. Communication between the gateway and the cloud uses MQTT over TLS to ensure lightweight and reliable message delivery.

The smartphone communicates with the cloud using REST API calls over HTTPS (TLS 1.2 or higher). Key endpoints include:

- `POST /api/v1/patients/{id}/sleepDiary`
- `POST /api/v1/patients/{id}/wearableData`
- `GET /api/v1/patients/{id}/therapyPlan`
- `POST /api/v1/patients/{id}/questionnaires`
  Authentication is managed through Bearer tokens (JWT), which are refreshed using the OAuth2 `refresh_token` flow.

A WebSocket connection is used for real-time updates, such as alerts when a patient crosses a threshold. The app also accesses REST endpoints similar to the patient's app but with extended scopes to allow clinicians to access any patient in their caseload. Additionally, secure messaging is implemented over HTTPS, with all chat messages stored encrypted at rest.

Server and Cloud Component

High-Level Architecture

API Gateway

This is the entry point for all RESTful requests from both patient and therapist applications. It enforces rate limits, validates JWTs, and routes requests to the appropriate microservices.

Authentication and Authorization Service

Acts as an OAuth2 provider using the Authorization Code Grant with PKCE for mobile apps. It manages user roles (patient, therapist, admin) and issues Json Web Tokens containing scoped permissions like `sleep:read`, `sleep:write`, and `therapy:modify`.

Ingestion Service

This service receives and processes various types of data: Sleep Diary JSON payloads, Wearable Summary data, Environmental Snapshot events, and Questionnaire Responses. It validates the schema, timestamps each entry, and stores the data in the appropriate database.

Processing & Analytics Service

Includes several subsystems:

- *Sleep Metric Calculator:* Analyzes raw 1-minute epoch data using algorithms like Cole–Kripke to determine sleep/wake states, and derives key sleep metrics (SOL, WASO, TST, SE).

- *Titration Engine (SRT):* Executes weekly via a CRON job at the patient's review time. It retrieves the past week's SE, applies adjustment rules, updates the PTIB in the relational database, and notifies the patient.

- *Environmental Correlator:* Correlates sleep data with environmental factors, such as identifying increased WASO when noise exceeds 50 dB between 2–3 a.m. Outputs are available via REST for therapist dashboards.

- *Engagement Engine (AI):* Uses unsupervised clustering to identify trends in adherence and SE. It flags patients at risk and can escalate notifications or alert clinicians.

Database

A combination of storage solutions is used:

- *Time-Series Data Store* (e.g., InfluxDB or TimescaleDB) holds wearable epoch data and environmental metrics.

- *Relational Database* (PostgreSQL) includes tables for users, patients, therapists, sleep diary entries, titration schedules, questionnaire responses, therapy adjustments, badges earned, and messages.

- *NoSQL Cache* (Redis) is used for storing ephemeral data such as session tokens, rate-limiting counters, and alert rules for quick access.

Notification & Messaging Service

Supports multiple communication channels:

- *Push Notifications* via FCM (Android) and APNS (iOS).

- *SMS/Email* through Twilio, particularly for critical alerts such as suicidal ideation.

- *In-App Chat* over a WebSocket server with encrypted chat logs stored in PostgreSQL.

Clinician Dashboard

A web-based dashboard hosted separately. It reads from both the relational and time-series databases. Authentication may include SSO integration with existing clinical systems for therapist access.

Admin Portal

Used for administrative tasks such as managing user accounts, therapist assignments, viewing system logs, running health checks, and exporting data (CSV or PDF) for research and audits.

Data Flow: Exemple end-to-end

Day 0: The patient completes their daily sleep diary, and the wearable device syncs data from the previous night.

Ingestion: The smartphone sends data to the server via `POST /sleepDiary` and `POST /wearableData`.

Processing: The analytics service calculates the patient's sleep efficiency (e.g., SE = 78%) and stores the result in the database.

Daily Feedback: The patient app calls `GET /therapyPlan` and displays feedback like, "Your SE last night was 78%—aim for 85% or above."

Weekly (Day 7 at 7:00 AM): The titration engine reviews SE from the past 7 days (e.g., 70%, 75%, 80%, 78%, 82%, 76%, 79% → average 77%). Since SE < 85%, the system recommends reducing PTIB by 15 minutes.

Update Schedule: The new PTIB is stored in PostgreSQL. For example, if the previous window was 12 AM–6 AM, it might now become 12:15 AM–6 AM.

Notification: The patient receives a push notification: "Your new sleep window starts tonight: Lights out at 12:15 AM, wake up at 6 AM."

Therapist Monitoring: The clinician sees the patient's SE (e.g., 77%) highlighted in red on the dashboard. They can review the patient's diary and wearable data for anomalies and optionally send a supportive message via the dashboard interface.

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