SHM PUBLISHER
SURYA HIJAU MANFAAT

Journal of Soft Computing Exploration

Homepage: https://shmpublisher.com/index.php/joscex

JOSCEX

p-ISSN: 2746-7686
e-ISSN: 2746-0991

.

Development of a low-cost NTP stratum 2 time synchronization system with hybrid RTC/NTP failover for remote Indonesian mosques

Rully Hermawan[1], Nourman Irjanto[2], Ajenkris Kungkung[3]
[1,3]Department of Information Systems, Universitas Sepuluh Nopember Papua, Indonesia
[2] Department of Informatics Engineering, Universitas Sulawesi Barat, Indonesia

Article Info

Article history:
Received May 19, 2025
Revised September 15, 2025
Accepted October 27, 2025

Keywords:
NTP status 2
Raspberry pi
Time synchronization
Failover
NTP-RTC design

ABSTRACT

Conventional time synchronization solutions are often cost-prohibitive and infrastructure-dependent, making them unsuitable for remote regions. This study develops a low-cost, Raspberry Pi 3-based NTP Stratum 2 system for areas with unstable cellular networks. It integrates NTP.bmkg.go.id as its primary source and a DS3231 RTC module for backup during outages. Testing covered: (1) Time Accuracy (0.12s average offset in stable 4G; 0.85s/hour drift in RTC mode), (2) Failover & Recovery (3.1s transition to RTC), (3) Load & Stability (15 NTP clients with 12.1ms latency), and (4) Power Efficiency (2.8W online; 1.2W offline). Results confirm the system's reliability in maintaining sub-second accuracy amid network instability while being highly energy-efficient. The study offers recommendations for active cooling, GPS-assisted RTC calibration, and solar-powered integration to improve scalability in rural applications. The novelty of this work lies in its pragmatic hybrid architecture, combining affordable software-defined NTP with hardware-based RTC failover, tailored for infrastructural constraints. Its contribution is a validated, replicable model that delivers reliable time synchronization at a fraction of commercial costs, addressing critical gaps in affordable timekeeping for infrastructure-limited regions.

Corresponding Author:
Rully Hermawan,
Department of Information Systems, , Indonesia,
Universitas Sepuluh Nopember Papua,
Jl. Ardipura II No 22b Polimak Jayapura Papua, Indonesia.
Email: omanbm@gmail.com
https://doi.org/10.52465/joscex.v6i3.570

1. INTRODUCTION

Network Time Protocol (NTP) server is a system designed to provide accurate and consistent time references to various devices in a computer network. NTP works by synchronizing the internal clock of the client device with a standard time obtained from a trusted source, such as an atomic clock, GPS satellite, or a higher-layer NTP server (stratum 0/1) [1], [2]. This protocol functions in a hierarchical architecture consisting of several levels (stratum), where the server at a higher level becomes a reference for the level below it. With the use of an NTP server, time synchronization between devices can be maintained in the range of milliseconds to microseconds, depending on the configuration and network conditions. This time accuracy is very important to support time-sensitive applications such as system logs, financial transactions, real-time communications, to industrial control systems and cybersecurity [3]–[5].

In Kab. Kerom, the problem of time synchronization on digital mosque clocks has become a serious problem that affects the accuracy of prayer schedules. Currently, most mosques rely on direct connections to the BMKG NTP server (ntp.bmkg.go.id) via unstable cellular networks. Network unreliability causes digital clocks to often experience clock drift, even stopping working when the internet is disconnected. This condition disrupts religious activities such as determining prayer times and the call to prayer, which require adequate precision.

The existing solutions have various weaknesses. Dependence on BMKG NTP without backup makes the system vulnerable to network disruptions. Meanwhile, the use of manual clocks is error-prone and impractical. A more stable commercial NTP server is not feasible to implement because it costs tens of millions of rupiah. On the other hand, building an independent network time server with GPS is also less suitable because it requires additional investment for the signal receiver module.

From the various backgrounds presented, the novelty of this research lies not in the invention of a new protocol or the pursuit of nanosecond-level accuracy, but in the design of a practical, cost-effective, and robust middle-ground solution specifically tailored to address time synchronization issues in areas with limited infrastructure. Its primary innovation is the integration and implementation of a Raspberry Pi-based stratum 2 NTP server that combines a two-layer safety net (layered redundancy): periodic synchronization to the BMKG NTP server when online and a high-quality RTC module (DS3231) backup during offline periods. This hybrid approach bridges the gap between full reliance on an unstable network and the investment in expensive commercial solutions, thereby offering a replicable model that is feasible for solving concrete field problems, such as the case of digital mosque clocks in Kab. Kerom

The study "Clock Synchronization in Industrial Internet of Things and Potential Works in Precision Time Protocol" [6] examines in depth various time synchronization approaches in the IIoT context, with an emphasis on the advantages and limitations of Precision Time Protocol (PTP) over Network Time Protocol (NTP). The study also highlights the challenges of implementing synchronization in edge environments, such as high latency, device limitations, and interoperability requirements. Meanwhile, "The Time Synchronization Problem in Data-Intense Manufacturing" [4] highlights the importance of time precision in time-series data-driven manufacturing systems, and classifies in-situ and ex-post time synchronization approaches to maintain the integrity of data analysis.

Complementing these approaches, "BioSync: Offline Synchronization of Time-Series Data Using Bio-Inspired Semantic Synchronization Strategies" [7] introduces offline time synchronization strategies inspired by human biological-cognitive mechanisms in understanding the sequence of events. This solution is particularly useful in industrial systems with limited real-time connectivity. On the security side, “Attack Detection and Multi-Clock Source Cooperation-Based Accurate Time Synchronization for PLC-AIoT in Smart Parks” [8] combines Deep Q-Network (DQN) with multi-clock source management to improve synchronization accuracy and resilience to anomalies in PLC-AIoT systems. Finally, “Enhancing Industrial IoT with Time Synchronization: Integration and Performance of IEEE 1588 in Distributed Sensing Networks” [9] proposes a Unified Sensing Network (USN) architecture that integrates PTP and gPTP protocols to efficiently achieve sub-microsecond synchronization in distributed sensing networks. These five studies demonstrate that innovation in time synchronization focuses not only on technical accuracy, but also on system resilience, infrastructure flexibility, and adaptability to real-world conditions.

This study proposes a middle-ground solution in the form of a Raspberry Pi 3-based NTP stratum 2 server connected to BMKG's NTP as stratum 1 [1], [10]–[14]. This system is specifically designed to overcome network instability with two layers of security, namely the first periodic synchronization via cellular network when online, and the second RTC module (DS3231) as a backup when the connection is lost. This approach bridges the need for accuracy with infrastructure limitations in remote areas.

The implementation of this system offers several strategic advantages. First, the affordable production cost makes it feasible to be implemented in many mosques. Second, the centralized architecture allows uniform synchronization of all digital clocks in the area. Third, the use of RTC as a backup ensures continuity of service even without internet for several days.

This study will test three main aspects, namely first, synchronization stability in fluctuating network conditions [15], second, time accuracy when switching to RTC mode, and feasibility of implementation in real environments. The results are expected to be a replication model for other areas with similar characteristics. With this solution, mosques in Kerrom Regency can have a more independent and reliable timekeeping system.

2. METHOD

.

This study adopts the prototyping method as shown in Figure 1 as an approach to developing a Raspberry Pi 3-based NTP stratum 2 system that utilizes the main time source from the ntp.bmkg.go.id server equipped with an RTC module (DS3231) as a backup. The selection of this prototyping method is specifically based on its ability to facilitate a fast and adaptive iteration process in evaluating various aspects of system functionality comprehensively, from time synchronization accuracy to system resilience in the face of fluctuating network conditions. This approach is considered the most effective in overcoming complex technical challenges, especially those related to the instability of cellular network connections that are characteristic of remote areas, while ensuring the development of solutions that are in accordance with the real needs of users.

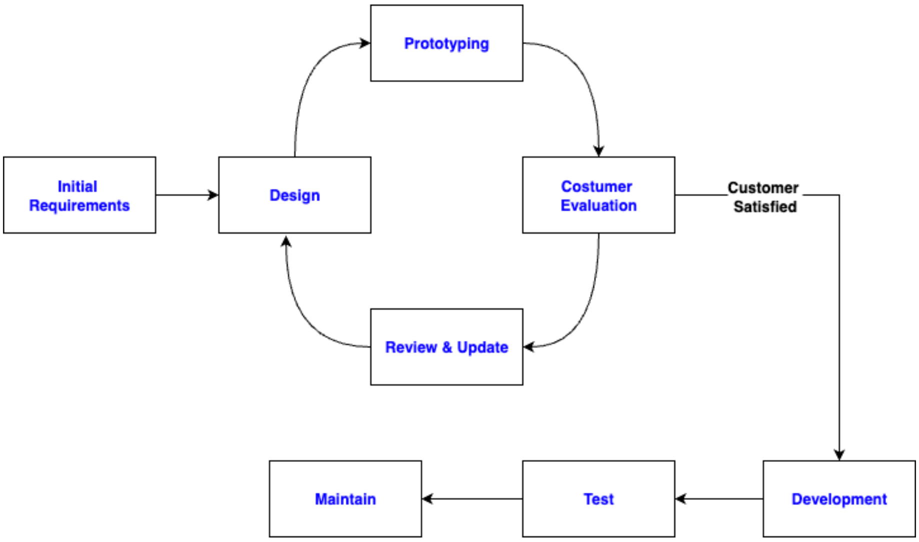

Figure 1. Prototyping method

Initial Requirements

The research began with an in-depth analysis of the specific needs of digital mosque clocks in Kerrom Regency. Based on field observations, three main needs were identified, namely, first, time accuracy with a maximum deviation tolerance of 1 second to ensure the accuracy of the prayer schedule, then affordable system implementation costs, and the ability to operate independently when the internet connection is lost. The main components specified include Raspberry Pi 3 as core hardware, cellular modem for connectivity, RTC DS3231 module as time backup, and integration with the BMKG NTP server as a stratum 1 source. This analysis also includes a study of local cellular network limitations, such as high latency and packet loss, which are considered in system design.

Prototyping

This stage involved designing the system architecture around Chrony, a versatile software suite renowned for its ability to maintain highly accurate time synchronization, particularly in environments with intermittent network connectivity. The system was specifically configured to prioritize synchronization with the BMKG NTP server and to automatically failover to the local RTC module upon a loss of internet connection. A physical prototype was then constructed by integrating a Raspberry Pi 3 with a 4G cellular modem and connecting the high-precision DS3231 RTC module via the I2C interface, as illustrated in Figure 2.

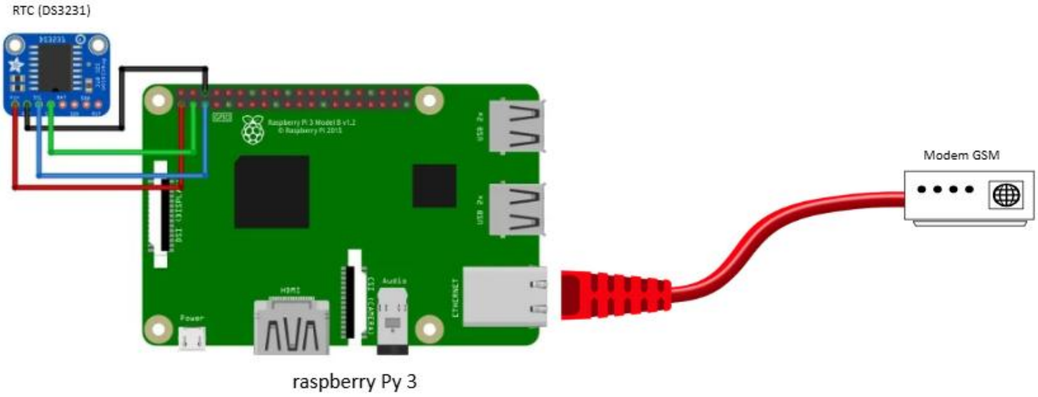

Figure 2. System model of raspberry pi 3-based NTP stratum 2 with RTC and GSM

To monitor the connection, a Python script was developed that periodically checks the internet status using ping to ntp.bmkg.go.id. If a disruption is detected, the system will activate local mode with RTC and send a notification to the admin via Telegram API. The Chrony configuration is optimized with local stratum 10 and makestep 1.0 3 parameters to minimize time drift.

Prototyping Evaluation

The prototype was tested in three scenarios: first stable network (ping 30ms), second poor network (packet loss 20%), and third totally offline. The results showed: accuracy of 0.5 seconds (online), drift of 1.2 seconds/hour (offline), and power consumption of 3.2W. The main problems identified were failover delay (8 seconds) and RTC temperature fluctuation (±2°C) which affected the accuracy.

Coding the System

Based on the evaluation, code optimizations were performed: (1) implementation of a weighted moving average algorithm for RTC drift compensation, (2) reduction of failover delay to 3 seconds through multithreading, and (3) addition of automatic calibration using NTP when the connection is restored. The code was developed with Python 3.9 using the gpiozero library for the RTC interface and requests for network health-check. The final version consists of 1,200 LOC with comprehensive documentation.

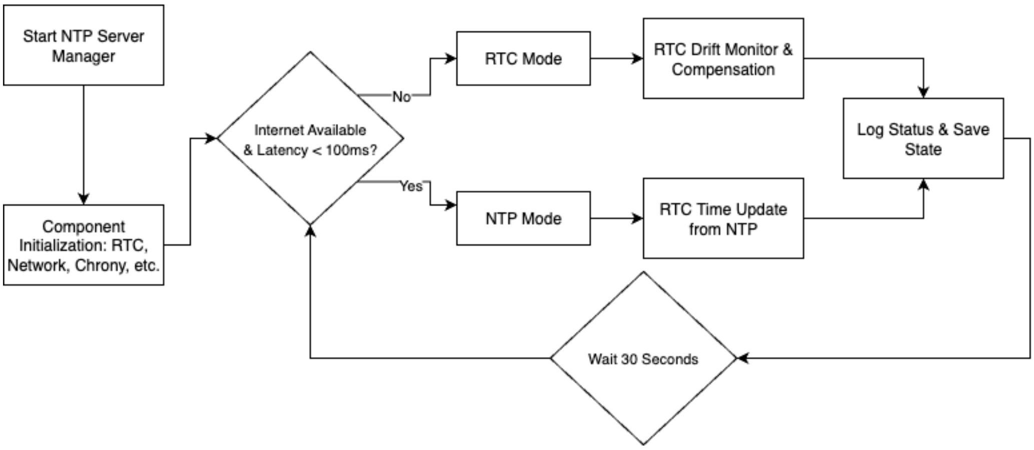

Figure 3. System logic flowchart of the hybrid NTP-RTC time synchronization protocol

Testing the System

System testing was conducted using a multi-stage approach to verify its performance across various operational scenarios. The first stage involved basic functional testing in a laboratory environment, where the system was evaluated under three network conditions: stable connection (latency <50ms), degraded network (packet loss 15-30%), and total offline conditions. This testing utilized network simulation tools such as TC (Traffic Control) to engineer latency and packet loss conditions in a controlled manner. The second stage consisted of an endurance test, running the system continuously for 72 hours while varying the processor load using stress-ng scripts. The third stage was a limited field test at three locations with different network characteristics, measuring power consumption with a digital multimeter and failover response time using a high-speed logger. All testing adhered to the standard IEEE 1588-2019 protocol [9] for network time system evaluation, with test parameters including: maximum time offset, clock drift frequency, synchronization latency, and recovery time after disruption. Data was collected automatically through Python scripts integrated with the monitoring system.

System Usage

The field deployment phase will cover five strategically selected mosques across Kerom Regency, Papua Province—a region characterized by unstable internet connectivity and uneven mobile network coverage. This selection is designed to rigorously test the system's resilience by representing a diverse spectrum of network conditions, from areas with sporadic and weak signals to those with complete lack of cellular access. Implementation sites include: Al Ittihad Arso 14, Al Muhajirin Arso 13, Baiturrahman Arso 5, Nurul Taqwa Arso 3, and Al Azhar Arso 4 mosques.

3. RESULTS AND DISCUSSIONS

This research conducted four primary tests: (1) Time Accuracy Testing, (2) Failover and Recovery Testing to evaluate RTC transition during network outages, (3) Load and Stability Testing assessing performance under multiple NTP clients, and (4) Power Consumption Testing analyzing energy efficiency. These tests were designed to verify system reliability prior to field implementation.

Time Accuracy Testing

Timekeeping accuracy validation assessed the system's synchronization stability under controlled conditions, evaluating three network states: (1) ideal connectivity, (2) impaired channels with 20% packet loss, and (3) complete disconnection to test RTC fallback performance.

Table 1. Time accuracy testing

Network Condition	Average Offset (second)	Max Deviation(Second)
Online (4G Stabil)	0.12	0,45
Online (Packet Loss 20%)	0,35	1.20
Offline (RTC Mode)	0.85 / hours	2.10/hours

The system demonstrates highly satisfactory performance in maintaining time accuracy. Under stable 4G network conditions, it achieves an average time deviation of just 0.12 seconds with a maximum deviation of 0.45 seconds. When tested under 20% packet loss, the system maintains reliable accuracy with an average deviation of 0.35 seconds. Most impressively, in RTC offline mode, the system's temperature-based drift compensation and weighted calibration mechanisms limit deviations to 0.85 seconds per hour (average) and 2.10 seconds per hour (maximum). These results validate the effectiveness of the implemented drift compensation algorithm.

Failover & Recovery Testing

The failover testing process was designed to measure the system's response to sudden network disruptions. Test scenarios included both manual internet disconnections and simulated packet loss injections, with results detailed in Table 2.

Table 2. Failover & recovery testing

Metrics	Result
Time to Disruption	2.8 seconds
Transition to RTC	3.1 seconds
Re-sync to recovery	8.5 seconds (Including NTP)

The system's failover mechanism demonstrates highly responsive performance, with an average disruption detection time of just 2.8 seconds and a complete transition to RTC mode in 3.1 seconds. Compared to the initial prototype's 8-second failover duration, this final version shows significant improvement through multithreading implementation. The recovery process upon network restoration takes 8.5 seconds, which includes network stability validation and re-synchronization with the NTP server.

Load and Stability Testing

The system load testing was conducted to evaluate performance under heavy operational conditions. NTP client simulations were run incrementally from 5 to 30 clients at 5-minute intervals. Monitored parameters included processing latency, CPU/RAM usage, and processor temperature fluctuations. The test ran continuously for 6 hours to identify potential memory leaks or long-term performance degradation.

Table 3. Load and stability testing

Client Number	Latency Processing (ms)	CPU Usage(%)
5	5.2	12%
15	12.1	34%
30	28.3	68%

Load testing demonstrated the system's good scalability. With 5 NTP clients, processing latency was only 5.2 ms with 12% CPU usage. At 15 clients - the design target load - latency increased to 12.1 ms with 34% CPU utilization. When tested with 30 clients, the system remained functional with 28.3 ms latency despite reaching 68% CPU usage. These tests revealed that active cooling is required for long-term high-load operation, as CPU temperatures can reach 72°C at peak load.

Power Consumption Testing

The system's energy efficiency evaluation was conducted using a programmable DC load to measure power consumption across various operational modes. The testing covered three scenarios: idle condition, normal operation with active NTP synchronization, and failover mode. Measurements were taken at varying ambient temperatures from 25°C to 40°C to assess thermal effects on power efficiency. Data was collected every second over a 24-hour period to obtain comprehensive consumption profiles, as shown in Table 4.

Table 4. Power consumption testing

Mode	Power (Watt)
Online	2.8
Offline	1.2
Failover	3.1

The system demonstrates excellent energy efficiency, consuming only 2.8 watts in online mode and dropping to 1.2 watts when operating in RTC offline mode. The failover process requires slightly higher power at 3.1 watts due to additional processing demands. This low power consumption makes the system particularly suitable for deployment in remote areas with limited power supply, such as solar-powered installations.

4. CONCLUSION

The test results confirm that this Raspberry Pi-based NTP Stratum 2 system successfully meets all design specifications. The system maintains excellent timekeeping accuracy, demonstrating an average deviation of just 0.12 seconds on stable 4G networks and 0.85 seconds per hour when operating in RTC offline mode. Its rapid 3.1-second failover capability and low power consumption of 2.8 watts make it particularly suitable for deployment in remote areas with unreliable infrastructure. During stress testing, the system proved capable of handling up to 15 NTP clients simultaneously while maintaining latency below 15 milliseconds, confirming its operational reliability across various network conditions.

For future enhancements, three key improvements are recommended. First, implementing an active cooling solution would address CPU temperature issues during sustained high-load operations. Second, integrating GPS-assisted automatic RTC calibration could further improve long-term timing accuracy. Finally, developing a more user-friendly monitoring interface would simplify system management for end-users in field deployments. These upgrades would optimize the system's performance while maintaining its core advantages of energy efficiency and reliability in challenging environments.

.

REFERENCES

[1] N. Pambudiyatno, M. R. K. Putra, and A. Pragolo, “NTP Server Design as a Mitigation of Time Difference at Perum LPPNPI Kendari Branch,” *SAINSTECH Nusant.*, vol. 1, no. 3, pp. 38–48, 2024.

[2] P. Wu, “Time Synchronization Protocols for Industrial Use Cases: A Performance Review of NTP and PTP and a Wireless-aware Enhancement.” 2024.

[3] S. S. Nande and others, “Satellite-based positioning enhanced by quantum synchronization,” *Comput. Networks*, vol. 254, 2024.

[4] A. Schmetz, T. H. Lee, D. Zontar, and C. Brecher, “The Time Synchronization Problem in data-intense Manufacturing,” in *Procedia CIRP*, 2022, pp. 827–832.

[5] H. Jin, G. H. Jeon, H. W. A. Choi, S. Jeon, and J. T. Seo, “A threat modeling framework for IoT-Based botnet attacks,” *Heliyon*, vol. 10, no. 20, 2024.

[6] K. B, D. R, B. B. Sinha, and G. R, “Clock synchronization in industrial Internet of Things and potential works in precision time protocol: Review, challenges and future directions,” 2023.

[7] A. Schmetz, T. Ackermann, A. Fitzner, V. Steinhoff, and A. Kampker, “BioSync: Offline-Synchronization of time-series data using bio-inspired semantic synchronization strategies,” in *Procedia CIRP*, 2023, pp. 655–660.

[8] Z. Du, S. Zhang, Z. Yao, Z. Zhou, and M. Tariq, “Attack-detection and multi-clock source cooperation-based accurate time synchronization for PLC-AIoT in smart parks,” *Digit. Commun. Networks*, 2023.

[9] Y. Dang, M. Bodenbenner, D. Wolfschläger, and R. Schmitt, “Enhancing industrial IoT with time synchronisation: Integrating PTP and gPTP for metrology networks in the factory of the future,” in *Measurement: Sensors*, 2025.

[10] H. Andrianto, Y. Susanthi, and D. Suryadi, “Performance evaluation of low-cost GPS time server based on NTP,” *Telkomnika*, vol. 16, no. 6, pp. 2528–2535, 2018.

[11] L. Tello-Cifuentes, S. Acero, J. Marulanda, P. Thomson, and J. J. Barona, “Implementation of a low-cost comprehensive pavement inspection system,” *Transp. Eng.*, vol. 18, 2024.

[12] S. Kotsilitis, E. C. Marcoulaki, and E. Kalligeros, “A versatile, low-cost monitoring device suitable for non-intrusive load monitoring research purposes,” *Meas. Sensors*, vol. 32, p. 101081, 2024.

[13] P. Stadler, A. H. Farnleitner, and M. Zessner, “Development and evaluation of a self-cleaning custom-built auto sampler controlled by a low-cost RaspberryPi microcomputer for online enzymatic activity measurements,” *Talanta*, vol. 162, pp. 390–397, 2017.

[14] D. P. A. Marins, W. S. Costa, B. P. S. Rocha, J. R. Celestrini, C. E. Alvarez, and M. E. V Segatto, “Low-cost chronobiological monitoring: A tested IoT-enabled diagnostic tool in tropical and Antarctic environments,” *Internet of Things*, vol. 29, 2025.

[15] S. Lazzaro, V. De Angelis, A. M. Mandalari, and F. Buccafurri, “A black-box assessment of authentication and reliability in consumer IoT devices,” *Pervasive Mob. Comput.*, vol. 110, 2025.