Building Smart and Sustainable Cities

A Proposal for a Consensus-Based IoT Data Aggregation System Supporting Sustainable Development Goals

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Project Proposal: Consensus-Based Distributed IoT Data Aggregation System for SDG 9 & 11

Enhancing Smart and Sustainable Infrastructure

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Introduction

The ever-expanding Internet of Things (IoT) ecosystem has given rise to billions of devices generating continuous environmental, industrial, and urban data streams. Traditional centralized data aggregation models often encounter challenges related to scalability, latency, and single-point failures. This project proposes a consensus-based distributed IoT data aggregation framework, wherein multiple sensor nodes collectively agree on global readings through iterative local exchanges.

This system supports SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) by enhancing the resilience, efficiency, and sustainability of smart city data infrastructures.

Objectives

- **Design** a distributed IoT architecture using lightweight consensus algorithms.
- **Simulate** sensor nodes that collaboratively compute aggregate values (mean, sum, min, max).
- **Compare** the performance of distributed consensus with centralized aggregation.
- **Evaluate** metrics: latency, communication overhead, energy efficiency, and accuracy.
- **Visualize** convergence behavior and demonstrate scalability benefits.
- **Highlight** contributions toward SDG 9 & 11 through improved infrastructure design.

Methodology

System Design

- Each IoT node produces periodic sensor readings.
- Nodes communicate only with local neighbors and iteratively update their values using the average consensus algorithm, gradually converging to the global aggregate.
- Baseline centralized aggregation is simulated for comparison.

Dataset

- A synthetic dataset of 50–200 nodes with simulated environmental readings (temperature, humidity, or energy usage).
- Alternatively, data may be sourced from a public IoT dataset like the UCI Air Quality Data Set or Intel Lab Sensor Data (Kaggle).

Consensus Mechanism

Each node (i) updates its value (x_i(t)) at iteration (t) as:

$$x_i(t+1) = x_i(t) + \epsilon \sum_{j \in N_i} (x_j(t) - x_i(t))$$

where (N_i) are neighboring nodes and (\epsilon) is a small step-size. This iterative update continues until values converge to the global mean.

Evaluation Metrics

Metric	Description
Latency	Rounds required to reach convergence
Communication Overhead	Messages exchanged per round
Energy Proxy	Estimated energy via message count
Accuracy	Difference from true global average
Scalability	Performance with increasing nodes

Impact of IoT on Sustainable Development Goals

The integration of the Internet of Things (IoT) technology plays a significant role in advancing various Sustainable Development Goals (SDGs). Below, we explore how IoT contributes to specific goals and outline future enhancements that leverage IoT's potential for sustainable development.

SDG 9: Industry, Innovation, and Infrastructure

Contribution: IoT technology is pivotal in building **resilient** and **innovative infrastructure**. By deploying scalable IoT solutions, industries can enhance operational efficiency and reduce resource consumption. IoT devices collect and analyze data in real-time, enabling industries to make informed decisions that foster sustainable growth and innovation.

SDG 11: Sustainable Cities and Communities

Contribution: IoT supports the development of **sustainable smart city ecosystems** through efficient, decentralized data sharing. By integrating IoT solutions, cities can optimize resource

management, improve public services, and enhance the quality of life for residents. IoT facilitates real-time monitoring of urban environments, leading to smarter, more responsive city planning and management.

Future Enhancements for IoT in Sustainable Development

To maximize the impact of IoT on sustainable development, several enhancements are proposed:

1. Integration of Real IoT Datasets

Incorporating datasets from sources such as Intel Lab and Air Quality monitoring systems will enable more accurate and comprehensive analysis. Real-world data integration will enhance the reliability and effectiveness of IoT applications in various sectors.

2. Fault-Tolerant Consensus for Network Failures

Developing fault-tolerant consensus mechanisms is crucial for ensuring the robustness and reliability of IoT networks. By addressing network failures, these mechanisms will maintain seamless operations and data integrity, even in adverse conditions.

3. Secure or Blockchain-Based Consensus

Implementing secure or blockchain-based consensus models will enhance the security and transparency of IoT networks. Blockchain technology, with its decentralized nature, provides an immutable ledger that protects data from tampering and unauthorized access.

4. Visualization of Live Network Topology Evolution

Creating tools to visualize the live evolution of network topology will provide insights into network performance and help identify potential issues. Real-time topology visualization aids in better network management and optimization, ensuring efficient and reliable IoT operations.

By addressing these future enhancements, IoT technology can further its contribution to sustainable development, creating a resilient, innovative, and sustainable future.

CODE:

In [1]:

```python
# ================================================================
# Consensus-Based Distributed IoT Data Aggregation System
# Author: Nowshika Mirza. R
# ================================================================

import numpy as np
import matplotlib.pyplot as plt
import networkx as nx
import random
import pandas as pd

# ------------------------------
# Configuration
# ------------------------------
NUM_NODES = 50            # number of IoT devices
AVG_DEGREE = 3            # average connections per node
ROUNDS = 25               # consensus iterations
STEP_SIZE = 0.25          # epsilon for update rule
np.random.seed(42)

# ------------------------------
# Build IoT network graph
# ------------------------------
G = nx.watts_strogatz_graph(NUM_NODES, k=AVG_DEGREE, p=0.3)
initial_values = np.random.normal(loc=25, scale=5, size=NUM_NODES)  # sensor readings
true_mean = np.mean(initial_values)

# ------------------------------
# Consensus Algorithm
# ------------------------------
values = initial_values.copy()
history = [values.copy()]

for r in range(ROUNDS):
    new_values = values.copy()
    for node in G.nodes():
        neighbors = list(G.neighbors(node))
        if neighbors:
            neighbor_mean = np.mean(values[neighbors])
            new_values[node] += STEP_SIZE * (neighbor_mean - values[node])
    values = new_values.copy()
    history.append(values.copy())
```

```python
# ------------------------------
# Analysis & Visualization
# ------------------------------
history = np.array(history)
df = pd.DataFrame(history)
df.to_csv("consensus_results.csv", index_label="Round")

plt.figure(figsize=(10,6))
plt.plot(history)
plt.axhline(true_mean, color='red', linestyle='--', label='True Global Mean')
plt.title("Consensus Convergence of IoT Nodes")
plt.xlabel("Rounds")
plt.ylabel("Sensor Value")
plt.legend()
plt.tight_layout()
plt.savefig("consensus_convergence.png")
plt.show()

# Performance metrics
final_error = np.abs(values - true_mean).mean()
print(f"✅ True Mean: {true_mean:.2f}")
print(f"✅ Average Final Node Value: {values.mean():.2f}")
print(f"✅ Mean Absolute Error: {final_error:.4f}")
print(f"✅ Total Messages Exchanged: ~{ROUNDS * NUM_NODES * AVG_DEGREE}")
```

Visualization

- **Line plots** showing convergence of node values over time.
- **Bar charts** comparing message counts between centralized and distributed methods.
- **Heatmap** of correlation among nodes after consensus.

📈 Results Visualization

Consensus Convergence Plot

Each colored line represents a node's sensor value.

All nodes converge toward the **red dashed line** — the true global mean.

consensus_results.csv

1	Round	0	1	2	3	4	5	6
2	0	27.483570765056164	24.308678494144075	28.23844269050346	32.61514928204013	23.829233126383322	23.8293152152541	32.8960640775
3	1	25.674362788458424	25.19676055255301	28.29431048990062	30.965693794549463	24.623915874795813	23.703728392211847	31.8813414695
4	2	24.78513538419582	25.643654574209638	28.241039660813275	29.937623955888405	25.01302821314456	23.655061123992617	31.1859309785
5	3	24.380910174066393	25.861012811283366	28.128439561872213	29.263801636821274	25.204891855359655	23.636141384522034	30.6586828479
6	4	24.229886708626054	25.95942832545485	27.98693147741724	28.79555452177265	25.302896773033694	23.62497081950058	30.2246851151
7	5	24.208217666254512	25.99667351734655	27.83457146396637	28.44959170334137	25.35722704384088	23.612600652933033	29.8466844893
8	6	24.249720158443	26.002853779287523	27.681711750560765	28.178831132382623	25.391474716609878	23.596427090793597	29.5059504908
9	7	24.31917153418081	25.993569323091112	27.533994426879342	27.956329324790293	25.416215523222323	23.57663266657226	29.1928195726
10	8	24.39804473916714	25.976822737450853	27.394233151144682	27.76640379878849	25.4358500026616	23.554391608453088	28.9020467008
11	9	24.476841207548723	25.95665178937712	27.26357818038843	27.5997127881905	25.451990572730374	23.53102988053951	28.6305360366
12	10	24.55094422737875	25.935041265524983	27.142229207487276	27.450517656922326	25.46509462089969	23.507680840007172	28.3762430448
13	11	24.61836325901379	25.91292762850199	27.02986677092137	27.315152663742623	25.47521958638682	23.485184161665813	28.1376493114
14	12	24.67850103333386	25.89072447511839	26.925910114721603	27.19116472194917	25.48234778094992	23.46409404102625	27.9135146102
15	13	24.73147780129279	25.868594749845727	26.829668735674648	27.076826317370703	25.486507212722334	23.444728571049318	27.7027613702
16	14	24.77776119931916	25.846589379505225	26.74042918515804	26.970857128887197	25.487800856527187	23.42722778736913	27.5044211952
17	15	24.81796480789435	25.824715832688568	26.65750270241758	26.872262944787288	25.48639884805376	23.411606446912337	27.3176097281

7	8	9	10	11	12	13	14
28.8371736457645 44	22.65262807032524	27.712800217929825	22.682911535937688	22.671351232148716	26.20981135783017	15.43359877671101	16.3754
29.099699505481574	23.917671107226386	25.639278575136316	22.962666790510646	22.891597189611097	26.67516508550318	15.669051791891967	16.9843
29.076938456235013	24.34807297420387	24.59893604353841	23.310627643402253	23.078807297820916	26.752547134849713	15.997870911266324	17.3766
28.92269191662778	24.410788741537505	24.079312968572616	23.64589004694735	23.241390481184393	26.635840757180688	16.342558506795203	17.6597
28.712682612002418	24.327919798296282	23.82241079578749	23.937390493746747	23.382992507058983	26.42943754455171	16.67184517500132	17.8860
28.4837484951703	24.201542547669085	23.69867216573077	24.17743743191037	23.505732480489577	26.188993026337126	16.975401399949217	18.0814
28.25342681813866	24.075824952184504	23.64316966184051	24.368541036216783	23.61138611091192	25.94360762088761	17.251909989435983	18.2584
28.02972808547254	23.967661129598504	23.623380058341063	24.517022044707517	23.70172399738349	25.707928175706122	17.5035560287959	18.4235
27.816004044111573	23.881590861784144	23.622962608100753	24.630038496329803	23.778539108223526	25.48876644059173	17.73356686158449	18.5800
27.61336406941239	23.816933798363294	23.633625624790596	24.714306801439527	23.843586230972033	25.28872640277587	17.945179347727585	18.7294
27.421868111115252	23.77110675497012	23.651067791433427	24.775640319330428	23.898517121598093	25.10819481350248	18.141259119323877	18.8730
27.241110506902544	23.741097014085945	23.67296411823544	24.818864656682255	23.94483620478666	24.946433079940736	18.32420587529075	19.01128
27.070501650164964	23.724063790123317	23.69797285094809	24.84789212545196	23.98387895099421	24.802174181142103	18.495975022454786	19.1446
26.909400670065157	23.717541055329512	23.725249078879077	24.86585109272155	24.016807871359546	24.673946148761125	18.65813916523483	19.2734
26.757175326841818	23.719468061216904	23.75420794569435	24.875222716587846	24.044620048070744	24.560244183097474	18.811956593054653	19.3978
26.613226871160535	23.728153032336266	23.7844097028897	24.877965437934375	24.068161164637385	24.459618945896384	18.958433938694778	19.5182

Expected Outcomes

- Demonstrate that consensus-based aggregation achieves near-accurate results with reduced communication overhead.
- Validate scalability advantages for large-scale IoT deployments.
- Provide quantitative insights into how distributed intelligence supports smart city resilience.
- Contribute to SDG 9 & 11 by enabling efficient, robust IoT infrastructure.

Project Significance

This project bridges distributed systems and IoT data analytics, offering a practical simulation of collaborative sensor intelligence. By minimizing central dependency, it supports fault tolerance, energy efficiency, and real-time decision-making—crucial for next-generation sustainable cities.

Conclusion

The proposed Consensus-Based Distributed IoT Data Aggregation System is a forward step toward decentralized smart infrastructure. It aligns technological innovation with the United Nations' vision of sustainable urban development, ensuring inclusive, safe, and resilient smart ecosystems under SDG 9 & 11.