

A Secure Communication Process of Wireless Sensor Network Architecture for Smart Urban Environment Monitoring Applications

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Abstract—Wireless Sensor Network has been increasingly used for remote monitoring system and its adoption in increasing exponentially for larger application too. However, there are various challenges associated with both resource management and security that roots up when the deployment scale goes massive and distributed in order. The proposed system considers a case study of smart city management where the problems associated with data transmission and security has been addressed. This is carried out using the provisioning of urban environment monitoring system that is an essential system for smart city projects to assure the citizens' better-quality well-being. The scalable and effective urban environment monitoring system requires a seamless transmission of the data from the sensor nodes to the analytics engine. The existing architectures are more designed to suit very specifically the use-cases. As a contribution, the proposed system introduces a cost-effective architecture for environmental monitoring in urban zones of smart city named as a Smart Sensor Surveillance System (4S-UEM). The core idea of the proposed system is to offer a balance between resource efficiency and resilience secure communication in large scale deployment of WSN considering smart city as deployment and assessment area. The proposed system makes use of urban geographical clustering process in order to develop an organized structure of sensor nodes. Different from any existing studies, the proposed system introduces data analytical engine followed by secure routing using gateway. The design of the proposed system is carried out using layered architecture of the communication model targeting towards a cost-effective, energy optimal, and secure data transmission to the analytics engine.

Keywords—Wireless sensor network (WSN); sensors; smart city security; secure communication process

I. INTRODUCTION

Urban environment monitoring (UEM) is an essential requirement for smart city projects [1] [2] [3] for various control mechanism applications. All these applications require a Smart Sensor Surveillance System abbreviated as '4S'. There exist multiple technologies for setting up surveillance systems for acquiring the data of importance. The analytics of these data correlates with the environmental changes [4]. Such technologies include surveillance camera systems and ambient-based monitoring technologies that suffer scalability, reliability, and the efficient correlation among spatial-temporal information [5]. The use of wireless sensor networks (WSN) as: "4S for UEM," i.e., "Smart Sensor Surveillance System for

Urban Environment Monitoring," aims to overcome these challenges and limitations. Therefore, this research study aims to design a standard architecture of WSN that provides a generalized architecture to comply with the "4S for UEM" requirements. The rationale behind arriving at a classic WSN for various 4S-UEM applications is overcoming the bottlenecks of the limitations of the suitability of one application-specific architecture to another. Typically, the data acquisition and analysis of many environmental parameters that include: temperature, humidity, traffic density on the road, vibration exerted on public infrastructure, pH-values in water, and many more parameters which leads to building smart control system for smart home, transportation, the safety of building & bridges, and water quality management, etc. as an actual application required for the smart city projects. Fig. 1 provides a snap-view of "4S-UEM" based applications and the intrinsic requirement.

As seen in Fig. 1, the intelligent system based on the architecture of the 4S-UEM requires four essential characteristics to be met by the suitable design of the 4S-UEM, and those characteristics are: {Lifetime, Accuracy, Coverage, Reliability}. Another additional requirement apart from these four is secure communication so that the realization of the 4S-UEM applications becomes possible in a real-time context. This paper proposes analytical modeling of the design of secure transmission through 4S-UEM to ensure accurate, reliable, and secure communication with optimal coverage.

Intelligent System	Pollution Control	Performance Metric	Reliability
	Disaster Management		Coverage
	Public Safety		Accuracy
	Electricity Grid		Lifetime
	Infrastructure Health		
	Water-Supply & Waste Water		
	Transportation		
Smart Sensor Surveillance System for Urban Environment Monitoring (4S-UEM)			

Fig. 1. 4S-UEM based Applications.

II. REVIEW OF LITERATURE

This section describes various related work of design and development of the WSN based applications for assessing the methodological briefing of existing urban environment monitoring system (UEMS). The scope of the discussion is only limited to various resource optimization scheme which are considered as best scheme for resource management. It is because if the resource management is enhanced, eventually security scheme will be positively affected. The typical challenge in the UEMS faced is the issue of the optimal deployment of the sensor nodes that ensure maximum coverage and another is the secure communication. To provide a connecting link for transmission, a network of wireless sensor nodes is formed where a hierarchy of nodes as hop nodes, local and global sink nodes are the integral part of the WSN as static or dynamic WSN [6] depending upon the mobility of nodes and application requirements.

It is essential to consider a better network performance while designing the network deployment strategy with optimal coverage and connectivity [7]. The problem of the optimal coverage is formulated either as a greedy algorithm [8] or an integer optimization problem [9], which resembles the localization or placement problem of the facilities [10]. The sensor nodes' optimal numbers are computed using various methods like disk model, sector model, and geometry pattern model [11]. Whereas if the localization is known, then the problem of the optimal deployment in the Urban area of monitoring and deployment of WSN prefer an integer programming where popular method like i) divide-and-conquer, ii) simulated annealing, and iii) Genetic Algorithm, but these methods pose additional overhead of time complexity [12]. Irrespective of these methods, there exist some unique challenges for the deployment of the WSN for UEMS. Another important observation is that in most of the deployment, the base station's position is always fixed, which does not provide an optimal network performance [13].

There is no doubt that there are many research work being carried out towards secure routing in WSN with evolution of different methodologies and techniques. The existing methods are found to offer highly specific issue addressing scheme overlooking different challenges associated with the addressed issues. For an example, secure scheme cannot be only addressed using encryption but it equally demands resource management. Existing studies witness few direction of work aim like this integrated issue. Hence, the prominent research gap explored is that there are few studies which have linked practical energy retention with cost effective secure data aggregation in WSN considering challenging distributed and large scale area.

III. SYSTEM MODEL FOR UEM

To monitor the urban environment, changes concerning temperature (T), pollution (CO₂), and environmental parameters are significant for the meteorological department. The applications ranging from dairy farm monitoring to traffic management can be built on a generalized architecture: 4S-UEM, as in Fig. 2.

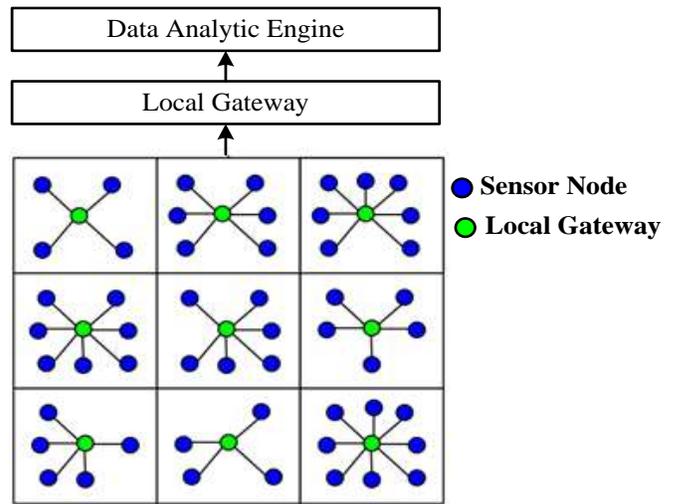


Fig. 2. Generalized Architecture 4S-UEM.

A. Sensor Node and Data Analytics Engine Deployment

An essential parameter in this part of implementation is basically number of sensors and simulation area. Introducing a data analytic engine is another contribution of proposed system which processes and analyzes the aggregated data unlike any existing clustering approach. The sensor nodes (Sn) are uniformly randomly distributed across a geographical area ($A = L \times L$) of deployment in the region to monitor urban locality. An explicit algorithm-1 ensures the optimal coverage and connectivity while deploying the sensor nodes (Sn), local gateway (Lg), and data analytics engine (DaE) as intrinsic units of 4S-UEM. The Sn's deployment is modeled as a graph: $G(V)$, where V is the vertex or a point that represents a Sensor node Sn.

Algorithm-1: Intrinsic unit deployment of 4S-UEM

Input: n, L, DaE

Output: $G(V)$

Process:

Start

for $\forall Sn_k \in n$

$[Sn.x, Sn.y] \leftarrow \text{frand}(n) \times L$

$G(V1) \leftarrow f([Sn.x, Sn.y])$

Initialize, {DaE.x, DaE.y}

$G(V2) \leftarrow f(\{DaE.x, DaE.y\})$

$G(V) \leftarrow G(V1) \cup G(V2)$

End

The WSN typically consists of 'n' number of sensor nodes (Sn) so that any sensor node ($'Sn'_k \in n$, s.t $2 \leq n$, where $n \in \mathbb{N}$ as a positive integer. The model takes 'n' and 'L' and 'DaE' as independent variables to get $G(V)$ as the dependent variable, i.e., $G(V) \leftarrow f(n, L, DaE)$. The adjustment of connectivity and coverage of Sn and DaE for optimization takes place with variations in its localization coordinates of Sn and DaE as $\{[Sn.x, Sn.y]\}$ and $\{DaE.x, DaE.y\}$ respectively. The normalization of a logical layer of the architecture of the 4S-UEM is as in the Fig. 3, while the model imitates the process of deployment.

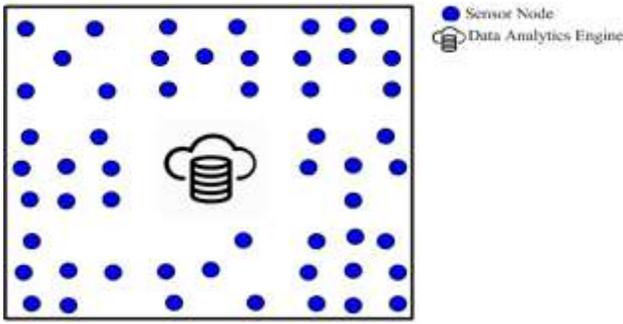


Fig. 3. Normalized Model Imitation for G(V) Containing Sensor Node and Data Analytics Engine.

B. Urban Geographical Clustering

In the smart city projects, the 4S-UEM synchronizes with the many sensor nodes deployed across the city or urban region by introducing an algorithm for Urban Geographical Clustering (UGC) to meet layer-wise communication that distance of communication is reduced. The prominent parameter of this part of implementation is local gateway which is responsible for performing translation services. The very basic requirement of UGC is to select a randomized local gateway (Lg) such that $Lg \in \{Sn\}$. A probabilistic approach considering the node's energy and the boundary conflict to avoid overlapping of spatial data overload is considered for the designing of UGC and selection of Lg. A straightforward process for the UGC is as in the algorithm 2. This approach establishes the communication between the lower layer of the sensor nodes or actuator with the local gateway.

Algorithm-2: Urban Clustering for 4S-UEM

Input:G(V)

Output:Cid, Lg

Process:

Start

Initialize, $nC \leftarrow \{m^2\}$, where $m \in \mathbb{N}$

$$\vec{D} = |(nC - nLg)|$$

$$[Vmin, Id] \leftarrow fmin(\vec{D})$$

$$\vec{B} \leftarrow fbound(id, L)$$

$$nC \leftarrow Id^2$$

$$\vec{S} = 1 \text{ to } nC \text{ with step } 1$$

$$\vec{S} \leftarrow freshape(\vec{S}, \sqrt{nC} \cdot \sqrt{nC})$$

for membership of $\forall Sn$ into an urban-Cluster

if

$$(Sn)_i.x \geq \vec{B}_i \wedge (Sn)_i.x < \vec{B}_{i+1} \wedge (Sn)_i.y \geq \vec{B}_i \wedge$$

$$(Sn)_i.y < \vec{B}_{i+1}$$

update: Cid for $\forall Sn$

end

visualize the urban clustering

Call algorithm for selection of Lg

Update: Lg in each communication cycle

End

The very basic assumption made while designing the architecture of 4S-UEM is that the number of local gateways (Lg) is as equal to the number of zones in the city or urban geographical region under monitoring i.e. $Lg = nC$, where $nC =$

number of urban clustering, which is taken as a set: $nC = \{m^2\}$, where $m \in$ a positive integer number. The nC is finally decided based on the node with energy and a probabilistic approach, where the boundary constraint \vec{B} . To compute Bc , initially, the difference of number of local gateways (nLg) and $nCas\vec{D}$ is computed as in equation 1.

$$\vec{D} = |(nC - nLg)| \quad (1)$$

Then, the index (Id) and minimum value (Vmin) from \vec{D} along with area component L goes to an explicit function to define the boundary as \vec{B} , which is a linearly spaced vector of L into $Id+1$ component, and the nC assigns as Id^2 . Further, a series \vec{S} as 1 to nC reshaped to the number of row and number of columns as \sqrt{nC} , say if $nC = 16$, then the \vec{S} is as below:

$$\vec{S} = \begin{bmatrix} 1 & 5 & 9 & 13 \\ 2 & 6 & 10 & 14 \\ 3 & 7 & 11 & 15 \\ 4 & 8 & 12 & 16 \end{bmatrix} \quad (2)$$

To get the membership of $\forall Sn$ into a specific urban cluster, the localization of each $(Sn)_i \in n$ is taken as basic parameters to define its class membership with the respective urban cluster based on the condition with the boundary constraints \vec{B} as in equation 3.

$$(\Sigma v)_i.\xi \in \vec{B}_i \perp (\Sigma v)_i.\xi < \vec{B}_{i+1} \perp (\Sigma v)_i.\psi \in \vec{B}_i \perp (\Sigma v)_i.\psi < \vec{B}_{i+1} \quad (1)$$

The corresponding identity to all the Sn is designated as cluster-id (Cid), with a potential of equal probability to be a Lg, and in this way, the urban clustering of all sensor nodes takes place, as seen in Fig. 4.

Section C describes the procedure for Lg selection along with the secure routing process as in Algorithm 3.

C. Secure Routing through Selected Local Gateway to the Data in 4S-UEM

The very objective of the optimality of the architecture of the 4S-UEM is to meet the energy balance of the nodes as well as the network with the consideration of the optimal routing in the least consumption of energy as well as the mitigation capacity for the data integrity against any kind of attacks which ensure the reliability of the data delivery for the analytics engine to provide the correct analysis on the real-time basis.

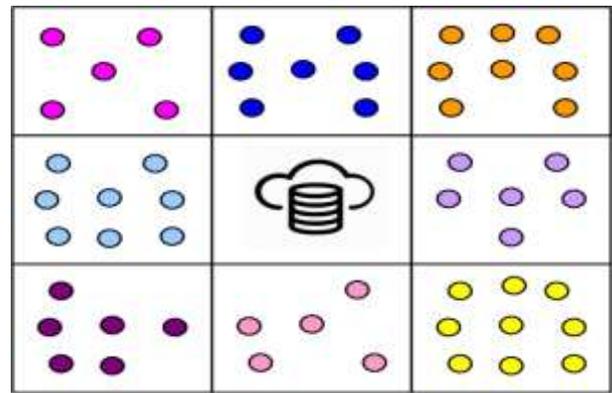


Fig. 4. Membership to each Sensor Node of 4S-UEM into an Urban Cluster.

Algorithm-3: Local Gateway selection in the Cluster of 4S-UEM and Secure Routing

Input: nC
Output: Lg
Process:
Start
Initialize the values of each in set:
 $P: \{Pl, cPl, Etx, ERx, Efs, Eamp, Ea, \}$
Setup process:
Initialize Pn
 $Po \leftarrow Rn1 \times Pn$
 $Pkc \leftarrow Rn2 \times Pn$
Generation of CG
 $[CG1, CG2] \leftarrow \text{farbitrary}(Pn, ID)$
Lg Selection process:
Initialize $\forall Sn P(Sn | Lg \rightarrow p \%)$
Update: Sn with energy in each communication cycle
 $ASn \leftarrow (nSn - nDSn)$
 $Lg \leftarrow G(ASn)$ based on Th
 $Th \leftarrow \frac{p}{1 - p \lfloor Ccxmod(\frac{1}{p}) \rfloor}$
Call data authentication process (Algorithm -4)
 Transfer the packets after integrity authentication to DaE
End

The system models take a set of parameters as independent variables, $P = \{Pl, cPl, Etx, ERx, Efs, Eamp, Ea, \}$, where: Pl = size of the data packet, cPl = size of the control packet, Etx and ERx are energy required for transmission and receiving respectively. Here Efs and Eamp are the respective amplification energy in case of free space communication or dense network deployment, whichever is the case. In many of the current work, it is found that, while designing the architecture of the communication over wireless sensor network, only a basic first radio model is considered with the transmission and amplification energy into consideration [14]. Whereas the system model of 4S-UEM also considers the energy required for the data to be aggregated or fused at the respective Lg \in uC (urban cluster) in the set of P, the performance resembles to the real-time constraints or context.

The characteristic of the sensor nodes (Sn) is a low capacity of computation and memory; thus, a lightweight security mechanism is proposed in the architecture of the 4S-UEM for the data authentication process in line with customized elliptical curve cryptography (ECC), while layer-wise communication. The first stage of this procedure is the setup stages as below:

- *Setup process:* In this process, the prominent parameter is a prime number (Pn) initiates to get the value of a primal Po as a product of a random number (Rn1) and the Pn and a public key center (Pkc) as $Rn2 \times Pn$, where Rn2 is another random number. An explicit function: *farbitrary()* is designed to take the Pn and the ID as an input argument to get the cyclic group. This operation's very basic function is to produce two cyclic groups (CG): {G1, G2} with a single element Pn such that it produces a set of the invertible values with a single binary operation of property associative. The

second stage of the system is the selection process of the Lg.

- *Local Gateway Selection Process:* In the Lg section's typical process, the Sn's energy plays a predominant role. The model validations occur with the varying probability of being Lg such that for $\forall Sn$ having $P(Sn | Lg \rightarrow p \%)$. Further, the cluster-id (uCID) for $\forall uC$ and the Sn whose energy (E) < 0 is marked as a node as fault or dead node ID as (DSn) and the total number of such dead nodes = $nDSn = \sum DSn$. Therefore, the sensor nodes Sn in each cycle of communications to be considered as the nodes with some energy as $(ASn) = nSn - nDSn$ is only considered to be set of the eligible Lg: $Lg: \rightarrow \{ASn\}$. The selection of the Lg from the set of {ASn} takes place based on a threshold node (Th) as in equation (4):

$$\frac{p}{1 - p \lfloor Ccxmod(\frac{1}{p}) \rfloor} \quad (4)$$

If the $Th <$ a random number between '0' and '1', the Sn \in ASn is treated as Lg from a group of G(Sn). In the equation 4, p = probability % of the ASn to be Lg, Cc = current communication iteration, $G(Sn) = \forall Sn \in ASn$ that has not been chosen as Lg in the last $(1/p)$ communication iteration. This threshold (Th) is considered in the state of artwork for hierarchical communication LEACH and its variance [15][16]. Unlike any another traditional approach, the rest of the Sn receives the broadcasted cPl and decides to be part of this Lg based on the energy-based signal strength. The communication process further in the 4S-UEM communication process goes for the data authentication, aggregation then transmission to the DaE as described into the algorithm -4. Fig. 5 illustrates the current stage as Sn, DaE, and urban clustering and selection of the Lg.

It is essential to integrate a data-authentication process in communication to ensure the correctness of the data reaching the DaE, so that correct analysis of the data of the environments records provides accurate input or instructions to the control systems. However, the trade-off here is to handle the timely delivery in optimal energy way as the sensor data collected from the various uC takes some amount of energy that influence the overall network lifetime.

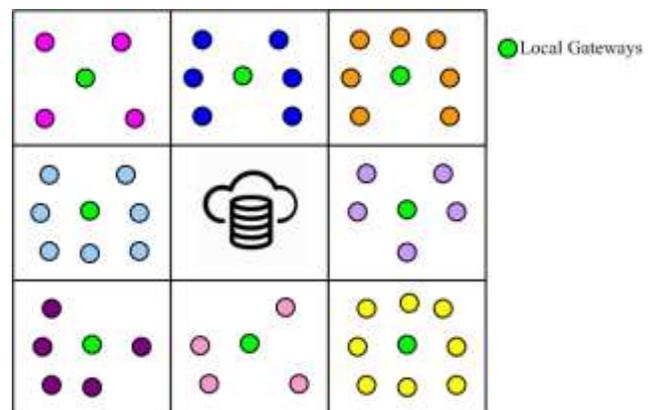


Fig. 5. Selection of Local Gateway (Lg) in the Urban Cluster (uC) of 4S-UEM Architecture.

The unique characteristics of the proposed communication process in the layer-wise approach of data from the individual sensors to the respective Lg and the aggregated or fused data transmission to the DaE in the optimal energy way even if the data gets authenticated by a very lightweight hashing mechanism of data integrity check within the sleep schedule cycle of the Sn, Lg, and DaE to avoid any kind of the collision, which is our future research direction to design an optimal tree-based routing for the channel resource allocation, which is beyond the scope of this stage of the architecture design. The details of the algorithm-4 are as below:

Algorithm-4: Data authentication, Aggregation, and transmission to the DaE as 4S-UEMSecure Routing procedure

Input:nC

Output:Lg

Process:

Start

Initialize, Id of Lg, and Id of ASn

$\forall ASn \in uC$, record messages as dP

$q \leftarrow \text{fhash-1}(\text{Id-ASn}, Pn)$

$[q, Pk] \leftarrow \text{fkeygen}(\text{Id-ASn}, Rn1)$

Initialize, Signing operation

Generate a Rn3

$P1 = Rn3 \times Pn$

$q1 \leftarrow \text{fhash-2}(P1, \text{Id-ASN}, dP)$

$u1 \leftarrow \sum [Pk, (Rn3 \times q1)]$

Update: Signature

$\text{Sig} \leftarrow \{P1, u1, \text{Id-ASN}, dP\}$

$sAm \leftarrow \sum mT \times \sum u1$

$CG \forall Lg$: mark Lg $\rightarrow 1$ based on Th

Aggregation Verification:

Call SPR

End

In this process, the Id of $\forall Lg$ gets initialized, and for each uC, Initially, the Id of Sn \in respective Lg is used for finding the ASn, and further, $\sum(ASn)$ participates in transmitting their data to the Lg for the aggregation process of the data packets. The secure aggregation process includes Lg selection, Sn data generation, signature verification, and routing simultaneously.

For $\forall ASn \in uC$, the respective data packet (dP) depends upon the application used in a signing process. An explicit function $fkg()$ takes the Id of ASn and Rn1 as used while creating the cyclic group in algorithm 3. The process of message authentication uses hashing algorithm in the key generation based on Id of ASn and Rn1, where $\text{fhash-1}(\text{Id-ASn}) \rightarrow q$, where $q = Pn \times \text{Id-ASn}$, which finally provides corresponding private key (Pk) for ASn using $Pk = Rn1 \times q$ using an explicit function $\text{fkeygen}()$. The next operation is the Signing operation, which takes $\{\text{Id-ASn}, dP, Pn, Pk\}$.

Initially, a random number Rn3 is generated in the signing process, which gives a first P1 as $P1 = Rn3 \times Pn$, which passes into $\text{fhash-2}()$, along with Id-ASN and dP, which gives a new hash value q1 as $q1 = dP \times \text{Id-ASn} \times P1$. Another, primal u1 is computed as in equation 5.

$$u1 = \sum [Pk, (Rn3 \times q1)] \quad (5)$$

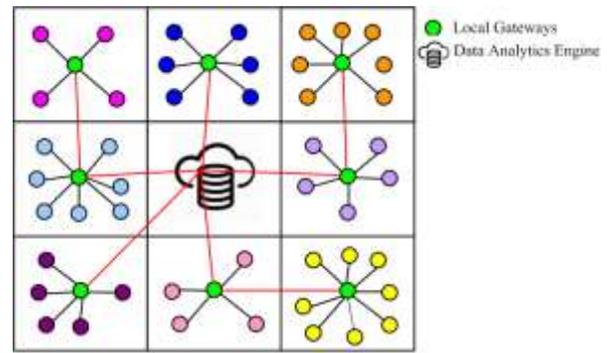


Fig. 6. The Transmission Process of Messages from uC through Lg to DaE of 4S-UEM.

Finally, the signature set includes $\{P1, u1, \text{Id-ASn}, dP\}$ and each intermediate computation stores in message-term (mT) as $u1 \times Pkc$, where Pkc comes from algorithm 3. Finally, $\sum mT \times \sum u1$ assigns as a signature for aggregate messages at Lg (sAm).

The cyclic group values of for $\forall Lg$ which do not participate in the selection, and the flag is set to zero for all Lg, and the process continues with the comparison of a random number between 0-1 and the Th as in equation 4. Finally, the aggregation verification occurs, and the system calls for the shortest path routing either from Lg to DaE or as inter Lg routing. Fig. 6 illustrates the data transmission process of the proposed 4S-UEM.

Fig. 6 clearly illustrates two layers of data transmission as proposed in 4S-UEM. The first layer of transmission takes place between sensor nodes (Sn) to the Local gateway (Lg) and the second layer of transmission takes place between the Lg to the data analytics engine (DaE). In Section 4, observations of energy variation and the network life are described to understand the model's behavior while imitating in a sequential numerical computation platform.

IV. PERFORMANCE EVALUATION

There are two scenarios to validate the model, and these scenarios are 1) Traditional [6]-[13] and proposed approach of data communication without the data aggregation process and 2) Traditional and proposed approach of data communication with data aggregation process. Fig. 7 to 11 represents the graphical representation of numerical outcomes in Tables I to V with an intention towards assessing scalability. The outcomes are represented in the form of energy parameters on y-axis with increasing number of sensors to represents the influence of performance parameters. The outcome shows proposed system with better energy compared to existing approach.

TABLE I. FIRST NODE DEATH AT NUMBER OF URBAN CLUSTERS = 4

No.of Nodes/ M	M1	M2	M3	M4
100	245	204	264	274
200	259	242	311	313
300	269	245	320	301
400	260	221	316	293
500	284	218	327	313

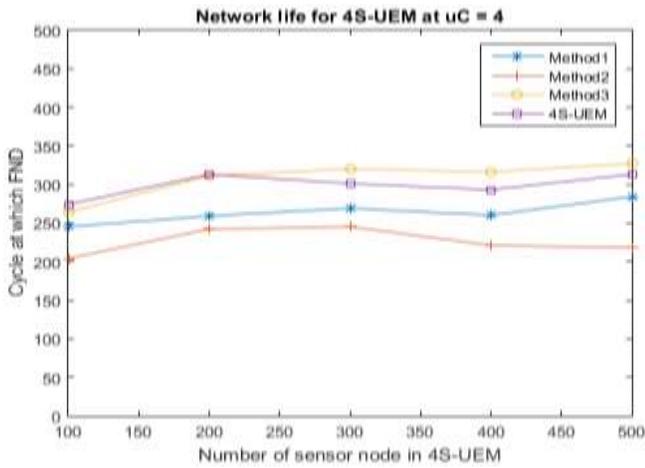


Fig. 7. First Node Death at Several Urban Clusters = 4.

TABLE II. FIRST NODE DEATH AT NUMBER OF URBAN CLUSTERS = 9

No. of Nodes/ M	M1	M2	M3	M4
100	106	123	117	170
200	240	119	259	225
300	250	142	289	224
400	262	151	309	203
500	261	142	312	209

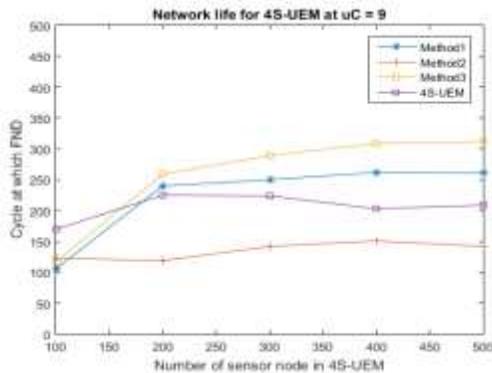


Fig. 8. First Node Death at Number of Urban Clusters = 9.

TABLE III. FIRST NODE DEATH AT NUMBER OF URBAN CLUSTERS = 16

No. of Nodes/ M	M1	M2	M3	M4
100	81	39	86	60
200	131	99	190	108
300	210	110	242	137
400	237	118	272	145
500	249	110	285	149

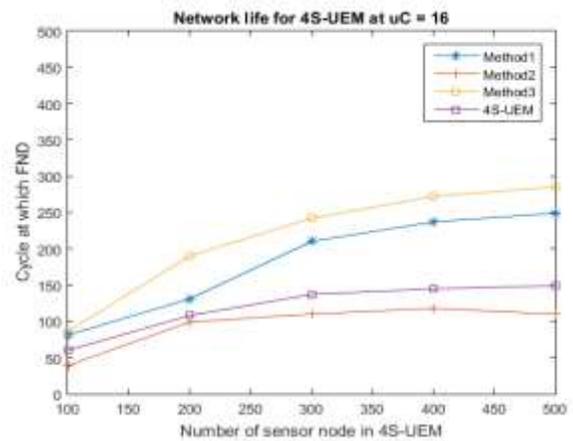


Fig. 9. First Node Death at Number of Urban Clusters = 16.

TABLE IV. FIRST NODE DEATH AT NUMBER OF URBAN CLUSTERS = 25

No. of Nodes/ M	M1	M2	M3	M4
100	80	39	80	82
200	103	99	82	69
300	85	110	150	107
400	167	118	228	100
500	210	110	246	104

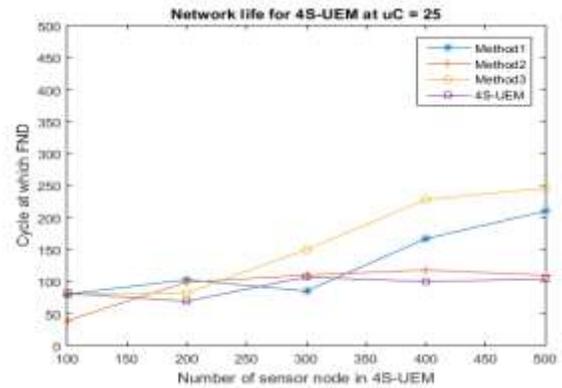


Fig. 10. First Node Death at Number of Urban Clusters = 25.

TABLE V. FIRST NODE DEATH AT NUMBER OF URBAN CLUSTERS = 36

No. of Nodes/ M	M1	M2	M3	M4
100	79	23	80	29
200	80	35	83	44
300	86	52	88	59
400	144	37	131	73
500	178	60	156	72

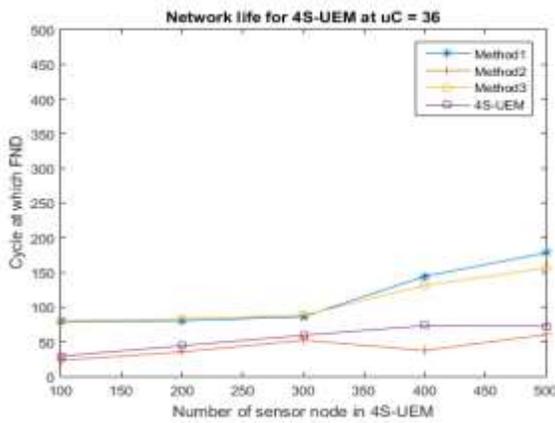


Fig. 11. First Node Death at Several Urban Clusters = 36.

V. CONCLUSION

The unified architecture proposed in this paper is named 4S-UEM, keeping in mind that to deploy a smart monitoring system for the urban environment monitoring purpose, the entire region of the urban zone is divided into the urban clusters where a local gateway is chosen smartly and intelligently. The local gateway collects the data and sends the data either directly or through inter-local gateway routing with the data verification provisioning. The important findings of this paper are i) proposed system offers approximately 47-58% of energy conservation over a large network of smart city, ii) The clustering model suits well with the public key encryption mechanism implemented unlike any existing methods, iii) the study offers no iterative scheme towards optimizing resources and hence it is highly cost effective. The 4S-UEM model provides a consistent result in terms of the network lifetime with a varying number of node density and the cluster. This work's future direction is to evolve a routing model so that priority-based routing takes place with further energy optimization during the channel allocation and avoidance of the collision of the packets utilizing optimal time slot scheduling of the radio.

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