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Optimized Service Embedding for Smart Buildings: Balancing Energy and Delay

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Abstract: *This paper presents a generic Mixed Integer Linear Programming (MILP) model designed to minimize overall power consumption arising from both processing operations and network traffic flow. The model is applied within a smart building context to explore energy-efficient and latency-aware deployment of IoT resources. The core problem involves identifying the optimal configuration of IoT nodes and communication links for embedding Business Processes (BPs) within the IoT infrastructure. Three distinct objective functions are considered: (1) minimizing processing and network power consumption, (2) minimizing average traffic latency, and (3) minimizing a weighted combination of power consumption and latency. The MILP formulation provides a structured approach to achieving optimal resource allocation while balancing performance and energy efficiency in smart IoT environments.*

Keywords*:* Mixed Integer Liner Programming(MILP), energy-efficient and latency

I. INTRODUCTION

An effective network structure is needed to mask device heterogeneity because IoT devices operate independently and differently from one another [8]. SOA provides a successful middleware solution to connect user applications with IoT hardware devices at the physical layer because it enables efficient communication across heterogeneous IoT devices [8]. This research evaluates the operation efficiency combined with traffic delay that results from implementing service requests in IoT building networks using SOA standards. The implementation of SOA-based middleware provides both node and network virtualization alongside multiple SOA advantages into a single framework.

A generic MILP mathematical model gets described in this chapter that targets power consumption optimization for network processes combined with traffic flow movements. The proposed model is used to build a simulation environment for a smart building scenario. The problem requires determining which IoT nodes and links should be embedded in the IoT layer to execute BP algorithms while optimizing three performance measures.

i) The model functions to minimize only the network together with processing power consumption levels.

ii) Minimizing mean traffic latency only

The optimization technique focuses on reducing the weighted summation of power usage alongside traffic delay.

The problem exists as a Mixed Integer Liner Programming (MILP) model.

II. PROPOSED ARCHITECTURE

In the smart building setting, many services employ IoT nodes such as:

Security services utilize motion detectors together with RFID technology and display screens and alarms systems.

The integration of motion detection together with temperature sensors allows energy saving services to operate effectively.

Smooth operation of fire protection systems depends on temperature sensors and smoke detectors and water sprinklers together with alarms.

Services in the entertainment sector use noise detectors and temperature sensors.

The administration services make use of motion detectors, temperature sensors, door actuators in addition to alarms.

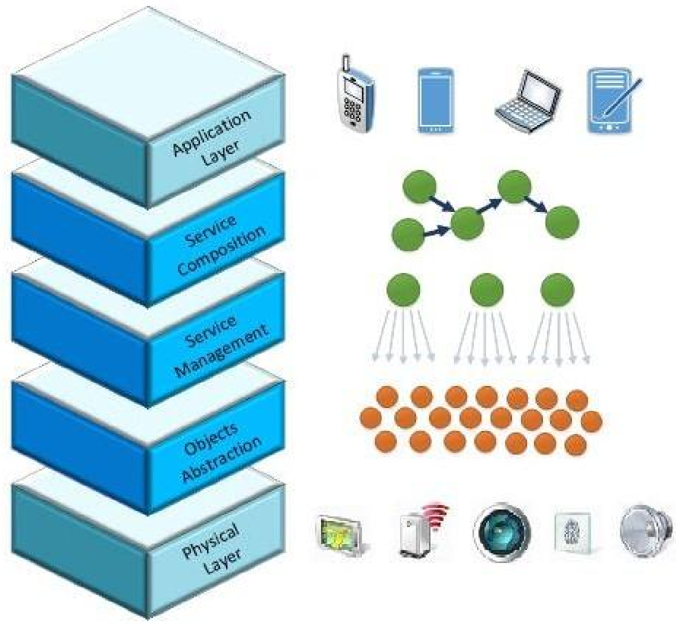

Figure1:SOA-based middle ware architecture for the IoT.

The same sensing and actuating facilities such as motion sensors and temperature along with sound devices and smoke detectors along with processing modules in IoT nodes can be used by various services. Multiple services are available through IoT yet an efficient architecture is necessary to hide device heterogeneity and ensure information interoperability when exchanging data with IoT devices. The SOA establishes methods for abstracting IoT node functionalities into basic operational services that afterwards developers can unite together for creation of complex upper-layer application interfaces.

The SOA middleware for IoT consists of three sub- layers illustrated in Figure 1 as per references [1], [2], [8].

The Objects abstraction layer lets IoT devices serve their functionality as basic services to upper layers.

Service management layer takes responsibility for two functions: dynamic object discovery and status monitoring available IoT node services.

Service composition layer functions as the location for business processes to request complex services through business processes (BPs). The description part of this system reveals how basic services work together in the workflow.

We create a service request embedding framework for networks built from IoT nodes. Programmers implement these requests at the SOA level through creation of BPs. A BP represents a topology design through which virtual nodes connect to other virtual nodes using virtual links. The virtual nodes contain both sensor and actuator functions along with processing needs as requested demands. Information transmission occurs between virtual nodes through the established virtual links. The embedding method transforms every virtual node and virtual link of each BP into nodes and links which exist within the IoT layer.

The BP design contains an array of virtual nodes and links for defining its structure. A virtual node has both processing requirements and memory needs for its assigned function. Each virtual node must receive assignment into an allocated geographic area. Traffic demands move from one virtual node to another through virtual links.

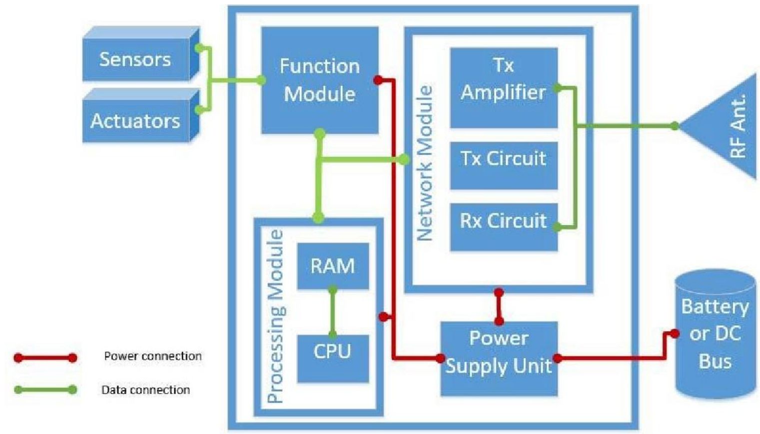

Figure 2: Block diagram of IoT Node.

The IoT node function consists of three core modules which are illustrated in Figure 2.

The processing module contains a CPU together with RAM as its central components.

The network module contains a wireless traffic transceiver with both a Tx/Rx circuit together with a Tx power amplifier.

The function module presents users with access interfaces for multiple sensors and actuators that the system supports.

Figure 3 shows how to embed two BPs into the network. The framework selects path (P1-P2-P5-P7) to establish communication between physical IoT nodes (P1-P2-P7) while embedding virtual nodes A1-A2-A3 of BP1 according to their respective IoT nodes P1-P2-P7. The framework decides to place virtual nodes inside IoT nodes that fulfill their technical specifications. Each IoT node containing a virtual node of any specified BP holds additional functionality to transfer data for other BP networks. The picture shows how IoT node P5 provides BP2 embedding functionality while handling BP1 traffic over the network.

In the analyzed typical IoT environment we focus on processing and network modules which use up the IoT node power yet sensing and actuating devices draw their energy independently from external power sources including the alarm and door locker.

The transmission speed between IoT nodes travels through multiple hop pathways where we examine both queueing and transmission delays that exceed propagation delays.

Traffic mean latency served as a performance measurement for networking systems according to the paper of [1].

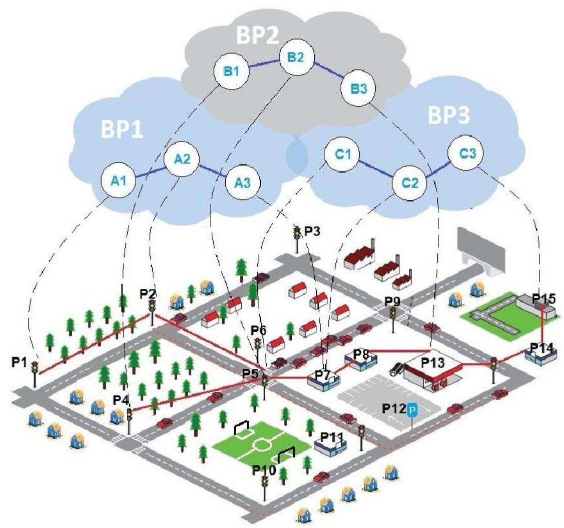

Figure3:Service embedding layers in IoT networks.

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III. RESULTS AND EVALUATIONS

A performance assessment of the proposed model together with its heuristic requires evaluating a smart building structure (such as an enterprise campus) composed of 30 IoT nodes connected through 89 bidirectional wireless links. The IoT nodes span 500 m x 500 m space with distribution assumptions for carrying different functional capabilities.

The model consists of nine separate functions with four sensor capabilities along with one control ability and four actuating capabilities. A single IoT node contains 2 sensing abilities together with 2 actuating capabilities and 1 controlling feature (which exists solely in a single processor type). A single function request is made through the virtual node of each BP.

The smart building consists of five geographical zones which serve as separate sub-sections of the enterprise campus (for example departments or sections). Six IoT nodes serve each geographical zone. All functions together with processor types appear in every defined zone. The virtual node submits a request for embedding placement within the five designated zones.

Six network microcontrollers with frequencies ranging from 8 to 48 MHz have been distributed uniformly to five processing capacities according to Table 4-1. Every virtual node has been assigned a processing requirement that ranges from 4 to 30 MHz.

The wireless transceiver modules are present inside all IoT nodes [2]. Each network module possesses low power characteristics along with low cost design that supports IoT network applications through the ZigBee protocol stack [209]. The virtual link traffic requirements extend from 50 packets to 200 packets per second with a standard packet size of 1 kb.

The sequential process considers two BPs simultaneously to embed a total of 12 BPs. BP contains three virtual components linked in sequence (sensor, controller and actuator) within each system. The sequence starts with the sensor unit which links to a controller unit and then the controller unit joins to the actuator unit. Virtual nodes require specific requests from sensors for data acquisition and controllers for processing capacity as well as actuators for execution functions. The sensor and actuator virtual nodes of a BP must have a specific zone location but the controller virtual node can reside in any geographical area.

MCU Type	MCU CLK	RAM	Idle Power	Max. Power
MSP430F1	8 MHz	64 kB	1 mW	8 mW
MSP430FR5	16 MHz	64 kB	1 mW	14 mW
MSP430FR6	16 MHz	128 kB	1 mW	20 mW
MSP430F5	25 MHz	512 kB	1 mW	14 mW
MSP432P4	48 MHz	256 kB	1 mW	16 mW

Table4-1: Processing modules power specifications and power consumption inactive mode

A MILP model serves to evaluate both power consumption and traffic mean latency during BP embedding when using the objective functions from Section 4.3.

4.3.1. Energy efficient service embedding

This section reviews how BPs perform regarding power consumption and traffic mean latency through three scenarios that utilize the objective function presented. The first scenario which we call energy-latency unaware service embedding (ELUSE) allows BP embedding on nodes and links without any emphasis on specific objective functions.

The goal in these two succeeding scenarios leads toward minimum total power usage. The process of re-provisioning involves re-embedding previous BPs when new ones arrive to the system in the second scenario whereas sequential embedding embeds new BPs without interrupting existing ones in the third scenario. The examination includes evaluation of embedding coexistence restrictions together with their influence on achieving energy efficient service embedding results.

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4.3.2. The service embedding process operates within the same geographic region.

The sensor along with actuator nodes of BP need to be situated within identical geographic areas according to this subsection. This research investigates two methods of embedding BPs while considering coexistence constraints or not. The virtual nodes of the BP cannot reside inside the same IoT node when coexistence constraints are active. This objective targets to enhance the BPs' resilience level in case of individual node failure.

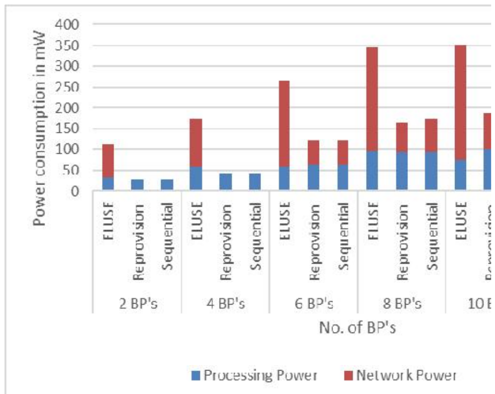

Figure4:The power usage of energy-efficient service integration in the same zone exists without restrictions for coexistence.

A total power consumption analysis stands in Figure 4-5 which includes the sensing and actuating nodes sharing one zone. The tested re-provisioning approach for energy efficiency cut down power use by 63% against the ELUSE methodology. Traditional BP embedding requires multiple IoT nodes and their corresponding links yet the energy-efficient method needs less nodes for performing BP embedding operations. The constitution of all BP virtual nodes within one IoT device limits local traffic and minimizes the operational number of active IoT nodes under this condition. The sequential embedding strategy cuts down energy efficiency by 58% from baseline since suboptimal placement occurred before adding new BPs.

As the number of embedded BPs increases their contribution to power saving becomes less significant. The network load influences the number of embedding solutions thus reducing the difference between energy-efficient embedding methods along with ELUSE.

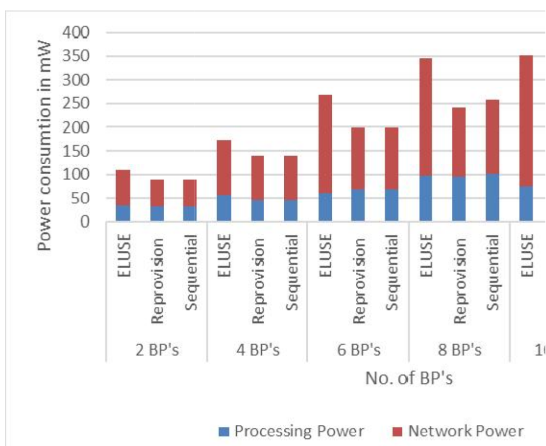

Figure5:Power consumption of energy efficient service embedding in the same zone with coexistence constraint.

The power usage for placing BPs within the same zone stands revealed in Figure 5 under stringent coexistence conditions. Coexistence constraints minimize power savings to 36% for re-provisioning while reducing them to 29% in sequential embedding environments. The power savings decrease when more IoT nodes need activation to fulfill coexistence requirements and when these nodes communicate with each other.

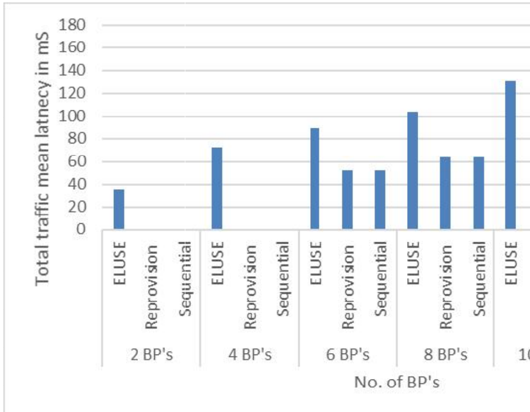

Figure 6: Without the requirement of coexistence constraint the energy efficient service embedding in same zone leads to average traffic mean latency measurements.

The measurements related to mean latency in traffic for BP networks appear in Figure 6 without enforcing coexistence constraints. The re-provisioning embedding together with the sequential embedding improved system traffic mean latency by 62% and 60% relative to the ELUSE scenario results. The traffic mean latency becomes lower when selecting minimum hops for energy-efficient embedding as compared to random routing in ELUSE. The traffic mean latency of energy efficient embedding exceeds its lowest possible values due to its mechanisms for maximizing activated IoT node usage.

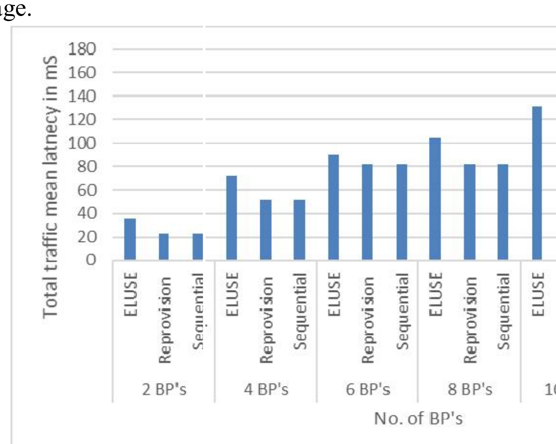

Figure7:The mean latency for traffic of energy efficient services embedding in the same zone under coexistence restrictions

Both re-provisional embedding and sequential embedding result in a 27% reduction of the average traffic mean latency in comparison to ELUSE embedding according to the Figure 7 data. The traffic mean latency achieves greater values when implementing BP at the same zone combined with coexistence constraints in comparison to embedding without coexistence constraints as Fig.7 confirms versus Fig.8 demonstrates. The traffic latency of a BP reaches zero value without coexistence constraints since virtual nodes are located within one IoT device.

4.3.4. Service embedding across geographical zone

The research found how power utilization and mean delay affected the BP embedding operations that needed sensor and actuator nodes placed at nearby locations. This section examines BPs with nodes that need to position in separate distant geographical zones. The analysis controls both performance levels under coexistence constraints and free of

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them at the controller node. Application of coexistence constraints causes the controller to lose its capability to place an IoT node together with either the sensor or the actuator node.

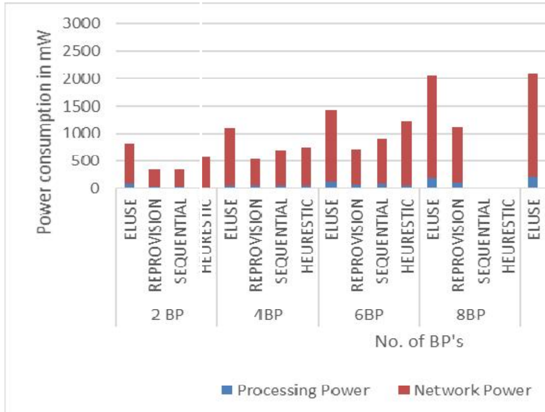

Figure8:Power consumption of energy-efficient service embedding occurs across different zones with no limitation on coexistence

The power requirements of BP embedding across different geographical areas are illustrated in Figure 8 when coexistence Between BPs is not a concern. Sequence-wise embedding under re-provisioning combined with different zones embedding yields inferior power reductions compared to the outcomes of Fig. 6 which deal with embedding within the same zone. The system fails to combine the sensor and actuator on the same node when performing energy efficient embedding across diverse geographical areas since coexistence restrictions do not exist. None of the energy-efficient embedding approaches fulfill their power conservation targets as effectively since they demonstrate a 42% savings under re-provisioning and only 22% savings under sequential embedding.

The inefficiency of resource usage in cross-zone embedding results in a sequential embedding capability of only 6 BPs although re-provisioning embedding continues to include 12 BPs.

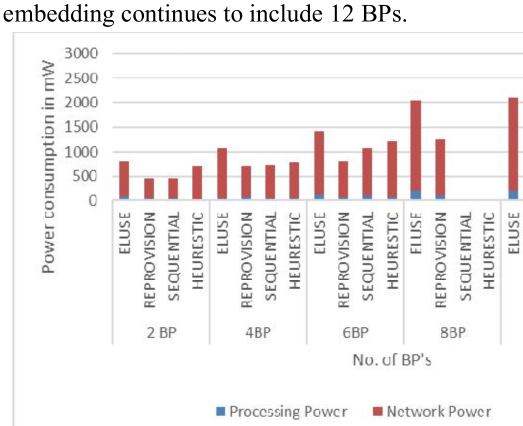

Figure9:Power consumption analysis for the placement of energy efficient services in different zones subject to coexistence restrictions.

The power consumption analysis for BP physical integration within an IoT network appears in Figure 9 under coexistence conditions. The power savings in energy efficient embedding become 34% and 17% when applying the re-provisioning approach or the sequential approach. The power reduction occurs because virtual BP nodes get placed across various IoT network nodes according to the previous explanation.

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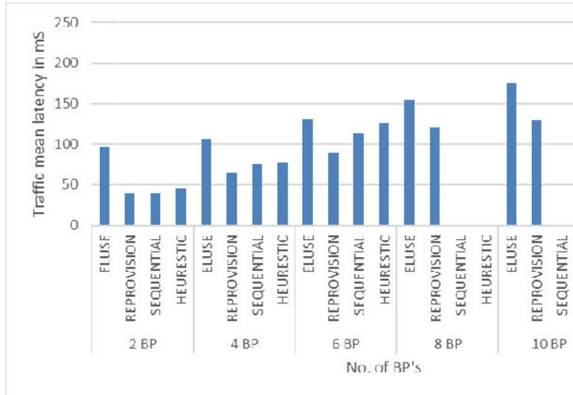

Figure10:The average delay of energy-efficient service placement occurs across different zones while maintaining independence between zones.

The Figure 10 depicts the traffic delivery times needed during BP connexions between various zones once exclusion protocols were included. Traffic mean latency decreased by 32% when the combination of re-provisioning with sequential embedding was applied.

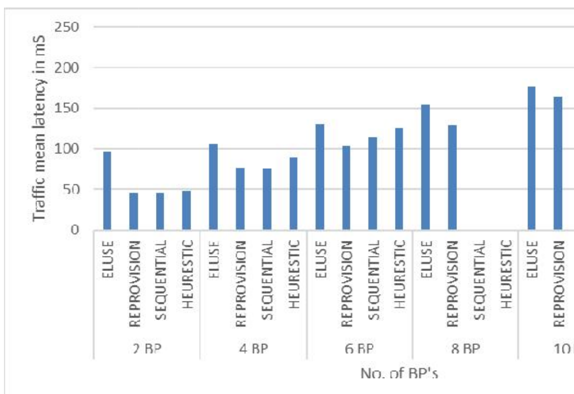

Figure4-11:The mean latency of energy-efficient service co-location systems operating across multiple areas under co-location restrictions.

There is an analysis in this section regarding the implementation of low-latency service in IoTnetworks.The BP embedding policy is analysed within different zones in terms of both power consumption levels and mean traffic latency as the objective criterion when coexistence constraints exist or do not exist.

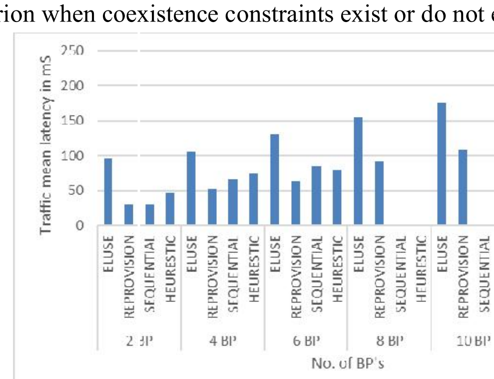

Figure4-12:The low latency service embeds across different zones achieves its average traffic mean latency without considering coexistence constraint.

The re-provisioning low latency embedding decreased traffic latency 47% on average when compared to results from the ELUSE scenario as illustrated in Figure 4-13. Virtual nodes are optimally selected through the low latency embedding model to distribute traffic in a way that minimizes arrival rates at nodes which subsequently minimizes traffic latency. The energy-efficient embedding process activates lower numbers of IoT nodes and links for BP embedding compared to the corresponding ELUSE scenario.

The sequential approach applied to energy efficient embedding reduces traffic latency to its original 20% under both conditions because the approach maintains prior embedding decisions found in Section 4.3.1. When resources were used optimally in re-provisioning the system managed to embed 12 BPs yet the sequential approach led to successful embedding of only 6 BPs.

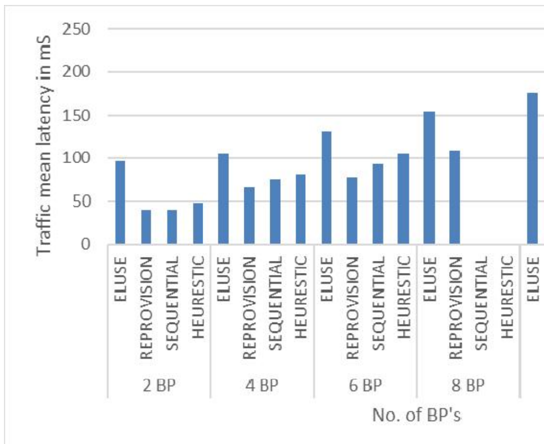

Figure4-13:The average mean latency for low latency service embedding spans across multiple zones when a coexistence constraint applies.

The mean latency measurements for low latency BPs traffic flow across different zones can be found in Figure 4-14 with coexistence restrictions enabled. Traffic mean latency increased by 34% for re-provisioning embedding and 19% for sequential embedding while the coexistence constraint was implemented making the network handle more traffic flow when multiple virtual nodes of the same blockchain prevent placement on the same IoT node.

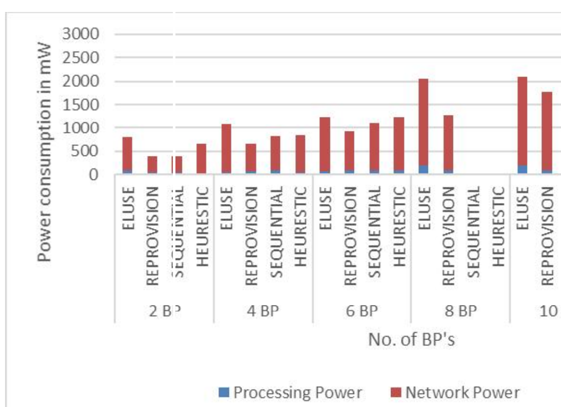

Figure4-14:Service embedding power consumption for low latency services between various zones operates independently without interfering with alternative use of these zones.

Results in Figure 4-14 demonstrate power consumption when embedding low latency distribution across different zones under non-coexistence conditions. The distributed traffic approach to reduce delay systems raised power consumption levels by 28% above the power optimized re-provisioning embedding in Fig. 9 since it needed to activate extra nodes.

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The power consumption of ELUSE decreases by 18% when using low latency re-provisioning and by 10% when activating low latency sequential embedding.

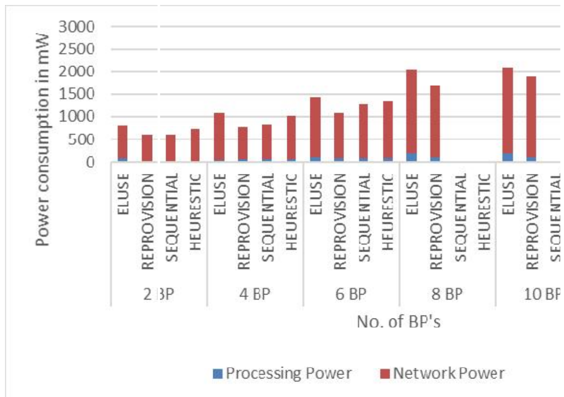
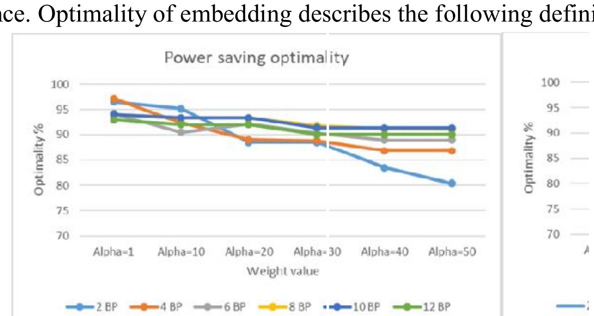


Figure4-15:The power consumption of low latency service embedding between different zones when zones share common resources.

The power consumption analysis revealed that coexistence embedding raised energy usage by 20% more than energy efficient re-provisioning embedding in Fig. 10 although both used the same premise as Fig. 10. erezithion to ELUSE results in lower power consumption of 14% for low latency re-provisioning coupled with sequential embedding.

An energy-efficient method of embedding low-latency service exists for IoT networks.

The minimum power consumption occurs when virtual nodes embed in as few number of energy efficient IoT nodes as possible. The achievement of minimum traffic mean latency depends on splitting the traffic across multiple paths to decrease incoming traffic at individual IoT nodes. Multiple-objective MILP model in Section enables the simultaneous minimization of power utilization and mean traffic delay according to sections. The measurement technique known as “embedding optimality” enables the evaluation of multi-objective embedding against single objective embedding performance. Optimality of embedding describes the following definition:



(A) (B)

Figure4-16:The model establishes optimality between power conservation and traffic latency in different zones under resource sharing constraints.

The optimization analysis of power-saving and traffic mean latency (Figure 4-16.A and 4-16.B) average optimality occurs throughout distinct zones with coexistence constraint under $\alpha = 30$, $\beta = 1$ and $\gamma = 1$ in the multi-objective function. The power consumption values remain similar to the traffic latency measurements so the weight α functions as the primary element to attain traffic latency optimization though other weights maintain a value of one. Under α=30 we reach an equal optimal level for power savings and mean traffic latency performance at 91%.

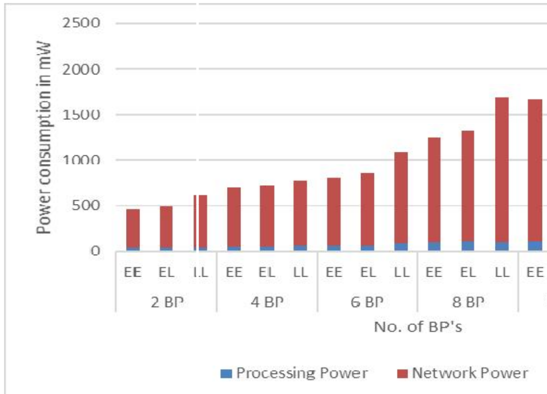


Figure4-17:When embedding in different zones with coexistence constraint requirements the power consumption becomes a factor to consider.

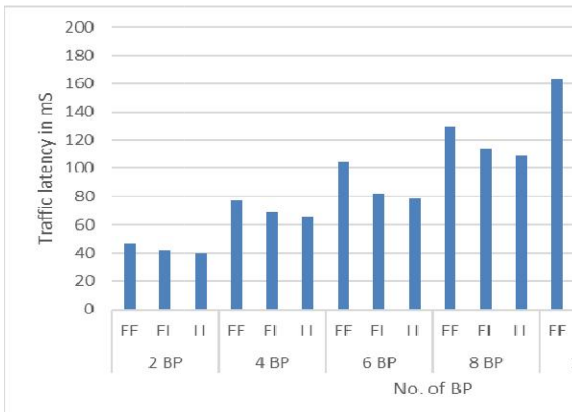


Figure4-18:Average traffic mean latency of embedding in distinct zones with Co existence constraint.

Figure 4-17 and Figure 4-18 present a comparison between power consumption and delay performance between the energy efficient–low latency service embedding scenario with $\alpha = 30$ and two other scenarios.

The power usage and delay parameters from all the scenarios were evaluated against $\alpha = 30$. Low latency scenarios cause power consumption to rise by 20% although energy efficient scenarios extend traffic mean delay by 22% compared to low latency scenarios (Figure 4-17, Figure 4-18).

The results presented in Figures 4-9 to 4-12 demonstrate that the embedding performance of RESE heuristic measures similar to sequential energy efficient MILP model across different zones. Table 4-2 presents the performance difference measurements between the RESE heuristic method and the sequential model through averages.

Table4-2:Power consumption gap

	2 BP's		4 BP's		6 BP's	
	Sequential MILP	Realtime Heuristic	Sequential MILP	Realtime Heuristic	Sequential MILP	Real time Heuristic
Processing Power	38	32	52	55	102	61
Network Power	451	784	692	811	1021	1322

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4.4. The real time low latency service employs heuristic availability

The RLSE heuristic method enhances traffic mean latency by implementing an optimizer threshold that manages node transmission capacity. The heuristic establishes traffic route optimization thresholds to maintain procedures under this level since it maximises distribution across various network paths.

Figure 4-13 through Figure 4-16 show that the new RESE heuristic performs equally well as the low latency model running sequentially on various zones. The average performance metrics obtained from executing the RLSE heuristic opposed to sequential model execution appear in Table 4-3.

Table 4-3: Traffic mean latency gap between the RLSE heuristic and the sequential model

	2 BP's		4 BP's		6 BP's	
	Sequential MILP	Real time Heuristic	Sequential MILP	Realtime Heuristic	Sequential MILP	Real time Heuristic
Latency	50	58	87	92	101	112

V. CONCLUSION

This part analyzed IoT-based smart building service embedding procedures by evaluating power consumption and traffic mean latency and introducing a minimization methodology. The service embedding process implements virtual node-link structures that implement workflows specified in Service-Oriented Architecture. Our research created an MILP framework and real-time heuristic method to select proper IoT nodes for virtual node placement and control virtual node traffic flows as it addresses three optimization goals between power usage minimization and latency minimization and power and latency dual minimization.

The BP deployment model studies sensor and actuator node arrangements through two specific zones which are designated as single-zonal deployment and multi-zonal deployment. The research investigated virtual node embedding techniques that did or did not enforce placement restrictions on individual IoT nodes.

The MILP model performed two optimization scenarios for maintaining BP embeds after network changes and delivering new BPs while active BPs continue their operations.

When using re-provisioning embedding technology for service implementation the power consumption efficiency improves over sequential embedding approaches. When using re-provisional embedding during the low latency service embedding phase the average traffic mean latency became lower than when using sequential embedding. A multi-objective optimization shows that BP embedding optimization reaches 91% power efficiency and reduces traffic latency at an optimum level.

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