Intelligent Learning and Computing Systems for Wireless Body Area Network-based Remote Healthcare

Thesis submitted in partial fulfillment
for the Award of Degree

Doctor of Philosophy

by

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I, ***Moirangthem Biken Singh***, certify that the work embodied in this Ph.D. thesis is my own bonafide work carried out by me under the supervision of ***Dr. Ajay Pratap*** from ***July 2021*** to ***October 2024*** at ***Department of Computer Science and Engineering***, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the researchers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc.* reported in journals, books, magazines, reports, dissertations, theses, *etc.*, or available at websites and have not included them in this thesis and have not cited as my own work.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Dedicated to

my beloved parents,

Moirangthem Mangijao Singh and Moirangthem O Muktamani Devi,

and

my cherished family members

ACKNOWLEDGEMENT

First and foremost, I would like to express my heartfelt gratitude to my supervisor, **Dr. Ajay Pratap**, for his invaluable support and assistance. I am eternally grateful for the opportunity to work on my thesis under his guidance. His constant encouragement and expert insights have been pivotal throughout my Ph.D. journey, fostering my critical thinking and providing feedback that has significantly enhanced my research.

I also extend my sincere thanks to all the members of the Department of Computer Science and Engineering for creating an excellent working atmosphere. My appreciation goes to my RPEC members, **Dr. Mayank Swarnkar** from the Department of Computer Science and Engineering and **Dr. Shyam Kamal** from the Department of Electrical Engineering, for their insightful comments and constructive suggestions that have refined my work. Additionally, I wish to express my gratitude to **Dr. Bhaskar Biswas**, Head of the Computer Science and Engineering Department, for fostering a supportive and inspiring environment for my research, as well as to all the DPGC members for their valuable suggestions and endorsement of this work.

I extend my heartfelt thanks to my lab mates—**Himanshu Singh**, **Shilpi Kumari**, and **Saurabh Kumar Mishra**—for their invaluable insights, collaboration, and shared knowledge. I am also deeply grateful to all my friends, including my Ph.D. colleagues, for their support and camaraderie throughout this journey. The relationships we have built have greatly enriched my research experience and made this time truly memorable.

Finally, I am profoundly grateful to my parents, **Moirangthem Mangijao Singh** and **Moirangthem O Muktamani Devi**, and my family members for their unwavering encouragement, love, and sacrifices that have enabled me to pursue my academic aspirations. With limitless humility, I would like to express my gratitude to the **Almighty** for bestowing upon me the favorable circumstances that have allowed me to achieve my life's goals during this pivotal juncture.

M. Biken Singh

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Symbol	Description
$\mathbb{P}$, $\mathbb{F}$	Set of patients/WBANs/WBAN users, and FSs
$\mathbb{S}$, $\mathbb{X}$	Sets of sensors and medical criticalities
P, F, S	Number of patients, FSs, and sensors
x_s	Medical criticality of sensor s and criticality level of patient p
θ_p^s	Health data sensed by sensor s from patient p
$\theta_{low,s}$, $\theta_{up,s}$	Lower and upper limits of health data collected by sensor s
$\mathfrak{s}_p^s$, c_p^s	Health severity and criticality index of sensor s's data
$SINR_p^f$, V_p^f, ω	SINR, number of allocated PRBs, and bandwidth of a PRB
$\mathbb{H}$, $\mathbb{P}^v$	Set of strategies and patients that violate latency constraint
u_p, q_p	Decision variables indicating whether LD or FS is selected
η_p, χ	Overall data size for p and revenue earned by MC
β_p	Required CPU cycles for computing p's data
$T_p^{c,l}$	Computation time for patient p by LD
$T_p^{tr,f}$, r_p^f	Transmission time and rate between p and f
$T_p^{c,f}(\mathbb{H})$	Computation time for a patient p at FS f
$\gamma_p(\mathbb{H})$	Fraction of FS f's resource utilized by p
$\mathbb{L}, \mathcal{V}$	Set of computation capacity of FSs and total utility
Υ, Γ_f	Computation capacity of LD and FS f
$\mathrm{n}'_{p,f}$	Number of patients using FS f, including patient p
$\mathrm{n}_{p,f}^{max}$	Max. no. of patients, including patient p, that can use FS f
$\mathfrak{m}$, l	Computation charge at FS and LD
ϕ, $\mathfrak{g}$	Expenses of MC and CPU cycle of FS
δ, k	Latency constraint and fixed charge per FS
$\Delta, \mathscr{H}$	Profit of MC and latency costs of patients
β_{max}	Maximum CPU required for processing patient health data
$l_{max}, \mathfrak{m}_{max}$	Maximum service charges for local and FS computation

Symbol	Description
$\mathscr{K}_{max}$	Maximum number of patients the CS can handle
$\mathrm{b}_p^s, \mathrm{y}_p^s$	Health data size and required CPU cycles for sensor s's data
$\mathcal{R}_s$	Priority or rank of sensor s's data from patient p
$\mathcal{M}$, $\mathcal{H}_s$	Highest and normalized priority or rank of sensor s's data
ψ, e_p^c	Effective capacitance, energy consumption of patient p
α_p, h_p^f	Cost per unit energy and choice of FS for patient
$\mathcal{E}_p^l$, $\mathcal{E}_p^{tr,f}$	Computation and transmission energy costs at LD for p
$\mathcal{C}_p^l$, $\mathcal{C}_p^f$	Latency cost to patient p at LD and at FS f
$\mathrm{e}_p^{tr,f}$	Transmission energy of p for sending its health data
n^f, F_f^{max}	Number of patients using f and maximum capacity of FS f
Π, Ω	Total latency and energy cost for all patients
υ, a, o	Cost and computation charges at FS and LD per megacycle
ν, ∂, Λ	Total revenue, expense and profit of HSP
η_{max}, β_{min}	Maximum data size and minimum required CPU cycles
$\mathcal{W}$, $\mathfrak{k}$	Utility function and transmit power of LD
λ_1, λ_2, λ_3	Positive weights of profit, latency and energy costs
W_p^f	Costs for patient p when FS f processes their health data
$\mathfrak{W}_p^f$	Profit of FS f for processing patient p's data
$\mathcal{L}_p, \mathcal{L}_f$	Preference lists of patients and FSs
$\mathbb{U}, \mathbb{N}$, $\mathbb{P}^f$	Sets of UAVs, PRBs, and patients assigned to FS f
$\mathfrak{J}_k^s$	Required number of PRBs based on throughput
$\mathfrak{T}_p^s, \varphi_p$	Required throughput and priority parameter of a WBAN
$\Im$, $\wp$	Number of sub-carriers and symbols per PRB
T_{sf}, $\mathscr{F}$	Frame duration and efficiency in bits/symbol
$\mathfrak{J}_p^{min}, \mathfrak{J}_p^{max}$	Minimum and maximum no. of required PRBs
$\rho_{th}, y_{p,u}^n$	Criticality threshold and binary variable
$\mathfrak{c}_u$, Φ_u	Computation capacity and coverage area of UAV
$\mathrm{r}_{p,u}^n, \jmath_{p,u}^n$	Data rate and SINR between WBAN p and UAV u on PRB n
$\mathbb{R}_{p,u}$	Achievable data rate between WBAN p and UAV u
$\mathrm{K}_p^{tr,u}, E_p^{tr,u}$	Transmission time and energy of WBAN
E_p, E_p^{init}	Energy consumption and initial energy of WBAN p
b_1, b_2	Positive weights assigned to criticality and energy
D_p, $\mathfrak{d}$	Number of data samples and price per health data sample
$\mathfrak{R}_p, \Theta_{p,u}$	Reward and revenue of WBAN p
$\mathbb{A}, \mathbb{B}$	Total revenue of all WBANs and all UAVs

Symbol	**Description**
e_u^{pd}	Power to balance skin friction parasitic drag
e_u^{rd}	Power to balance redirection drag force of air
$\mathrm{v}_u, \mathrm{L}_u$	Velocity of UAV and distance travelled by UAV
$\mathfrak{z}_u^{tve}, \mathrm{p}_u$	Traversal time and propulsion power of UAV u
ϖ_p, P_{cir}	Transmit power of patient and circuit's power consumption
$\imath$	Constant that depends on the efficiency of power amplifier
$\mathrm{E}_u^{tve}, \mathrm{E}_{u,p}^{rec}, \mathrm{E}_u^{tot}$	Traversal, receiving and total energy of UAV u
$\mathbf{w}^{(i)}$	Parameter of the FL model at global iteration i
$\mathfrak{F}_u(\mathbf{w}), \mathcal{A}, I$	Loss function, accuracy and no. of global iterations
$\mathfrak{b}_u$	CPU cycles per one sample data of UAV u
$\mathfrak{l}$	Step size or learning rate of model training
$\mathrm{E}_u^{com}, \mathrm{E}_u^{tne}$	Model computation and transmission energy
$\mathfrak{E}_{u,p}^{com}$	Energy consumption of UAV for model training
τ_u^{tnt}, $\mathfrak{j}_u$	Model transmission time and transmit power of UAV
l_u, H	Distance from UAV base to MBS and model parameter size
$\mathfrak{r}$	Time to send a unit data across a unit distance
$\mathcal{J}_p$	Reward of UAV for FL training on WBAN's data
$\mathscr{R}_u, O_u, N$	Reward, revenue of UAV u, and the number of available PRBs
$\mathfrak{f}_u, \mathcal{X}$	Unit cost of energy for UAV and total revenue
$\mathrm{G}(\mathbb{V}, \mathbb{E})$	Graph with set of vertices, $\mathbb{V}$, and edges, $\mathbb{E}$
k_u^n, $\mathbb{K}$	UAV-PRB pairs and set of UAV-PRB pairs
$e_{p,p'}$	Edge between WBAN p and p' in the interference graph
μ, $\mathfrak{C}$	Matching function and budget of model owner
R	Number of PRBs that can be allocated to elaborate WBANs
p^s, p^e	Steady and elaborate WBANs of WBAN p
$\mathfrak{L}$	Set of PRBs that can be allocated to elaborate WBANs
$C_{u,n}$	Set of WBANs that a resource pair has not yet applied
$\mathscr{Z}_{u,n}$	Set of WBANs with no edges between them in the graph
$\mathscr{Z}_{u,n}^{max}$	Set of WBANs after applying MWIS to $\mathscr{Z}_{u,n}$
$\mathbb{M}$, $\mathbb{G}$, $\mathbb{T}, \mathbb{Q}$	Sets of miners, reward levels, and two subsets of patients
M, G	Numbers of miners and reward levels
$\mathbb{D}_p$, $\mathfrak{n}_p^d$	Set of data samples and d^{th} data sample of WBAN p
$\mathbb{O}$	Set of MAC unit counts on WBAN chip
$\mathfrak{o}_p$	Number of MAC units on the WBAN p's chip
$\mathrm{h}, \mathrm{h}_{max}$	Precision level and max precision level

Symbol	**Description**
$\mathscr{O}_p(\mathrm{h})$	Energy consumption of WBAN p during local model training
$\mathcal{O}^{cm}(\mathrm{h})$, $\mathfrak{K}_p$	Computation energy and number of local iterations
$\mathcal{O}_p^{we}(\mathrm{h})$, $\mathcal{O}_p^{ac}(\mathrm{h})$	Access energy for weights and activations from memory
$\mathcal{O}_{MAC}(\mathrm{h})$	Energy consumption for a MAC operation with j-bit precision
$\mathfrak{P}_s, \mathfrak{P}_w, \mathfrak{P}_o$	Numbers of MAC operations, weights, and outputs
$\mathcal{O}_p^{comp}(\mathrm{h}), \mathcal{O}_{p,m}^{trans}(\mathrm{h})$	Energy for local model computation and transmission
$\mathfrak{O}_p^{comp}(\mathrm{h}), \mathfrak{O}_{p,m}^{trans}(\mathrm{h})$	Local model computation and transmission cost
$\mathscr{x}_p^d, \rho_p$	Severity index of $\mathfrak{n}_p^d$ and overall criticality level of a patient
$\mathscr{X}_{low}$, $\mathscr{X}_{up}$	Lower and upper bound of health data $\mathfrak{n}_p^d$
$\mathfrak{V}_{p,m}, \mathfrak{V}_{min}$	Data rate between WBAN and miner, and minimum data rate
$\mathfrak{p}_{p,m}$, $\mathfrak{S}_{p,m}$	Number of PRBs and SINR between WBAN p and miner m
$\mathbf{w}_{\mathfrak{Q}}, Enc(\mathbf{w}_{\mathfrak{Q}})$	Quantized and encrypted quantized local weights
$\mathfrak{q}_{p,m}^{trans}(\mathrm{h})$	Transmission time from WBAN p and miner m
$\mathfrak{w}_p$	Unit price of transmission energy of WBAN p
$\mathcal{Z}_{p,m}^g(\mathrm{h})$	Utility of WBAN p due to miner m with reward level g
$\mathfrak{B}_{p,m}^g(\mathrm{h})$	Reward of WBAN p from miner m with reward level g
$Y_{p,m}^g(\mathrm{h})$, $\mathfrak{N}_p(\mathrm{h})$	Decision variable and importance parameter of WBAN p
Q	Maximum mining reward provided by the blockchain network
$\mathcal{Q}_m(\mathrm{h})$	Revenue of miner m for adding blocks in I global iterations
$\mathfrak{t}_1$, $\mathfrak{t}_2$	Weights given to proportion of data samples and criticality
$\mathfrak{x}_m, \mathfrak{y}(\mathrm{h}), \mathcal{S}_m(\mathrm{h})$	Mining power, its unit cost, and the utility of miner m
$\mathbb{Y}, \Psi$	Association between WBAN p and miner m
$\mathcal{P}_p(\mathbb{M}, \mathbb{G})$, $\mathcal{P}_m(\mathbb{P}, \mathbb{G})$	Preference list of WBANs and miners
$\mathcal{F}$, $\mathcal{G}$	Subset of WBAN-reward level pairs, i.e., (p, g)
$\mathfrak{U}_m^{\mathcal{F}}(\mathrm{h})$, $\mathfrak{U}_m^{\mathcal{G}}(\mathrm{h})$	Utility of miner m associated with the pairs (p, g) in $\mathcal{F}$ and $\mathcal{G}$
$\mathfrak{M}_p$, $clip(w)$	Waiting list of WBAN p and weight clipping function
$loss(\mathbf{w}^{(p)}, \mathfrak{n}_p^d)$, $\mathbb{J}$	Loss per data sample and set of FL models
$\mathcal{I}_p(\mathbf{w}^{(p)}), \mathbf{W}^I$	Loss function for all data of WBAN p and optimal weights
ι	Smallest positive number that can be represented using j bits
$\mathfrak{Q}(w)$, $\mathbf{w}_{\mathfrak{Q}}^{(p,i)}$	Quantization function and quantized model weights for WBAN
$A, \mathrm{l}, \mathrm{j}$	Gradient bound and privacy parameters
$\mathcal{N}, \sigma$, $\mathbf{W}^{(i)}$	Gaussian noise, noise scale, and aggregated weights at iteration i
$\Delta\mathcal{I}_p(\mathbf{w}_{\mathfrak{Q}}^{(p,i)}), \mathrm{H}', \mathrm{H}''$	Gradient of loss function, clipped, and noise added gradients
$\mathcal{D}_m, \mathscr{D}$	Total data at miner m and total data of all associated WBANs
$\mathscr{A}_{p,j}^{\mathrm{i}}$	i^{th} health data sample of WBAN user p for FL model j

Symbol	**Description**
$\mathrm{I}_{p,j}$	Number of health data samples of WBAN user p for FL model j
$\mathbf{S}_{p,j}$	Local model parameters of WBAN user p for FL model j
$\mathrm{F}_{p,j}(\mathbf{S}_{p,j})$	Overall local loss function for all data samples of WBAN user
$\mathrm{Q}(\mathbf{S}_{p,j}, \mathscr{A}^{\mathrm{i}}_{p,j})$	Local loss function for a single data sample
$\mathscr{o}_{p,j}$	Noise scale of WBAN user p for FL model j
$\epsilon_{p,j}, \mathrm{f}_{p,j}$	Privacy parameters of WBAN user p for training FL model j
$\epsilon_j^{min}, \epsilon_j^{max}$	Minimum and maximum allowed privacy budget
$\mathrm{a}_{p,j}$	Accuracy of the WBAN user's local model for FL model j
$\top$	Conversion parameter from privacy budget to accuracy
$\mathcal{Y}$, J	Gaussian noise added loss function and number of FL models
$\mathscr{C}^{data}_{p,j}$	Cost for WBAN user p to collect $\mathrm{I}_{p,j}$ health data samples
$\mathscr{C}^{pri}_{p,j}$	Privacy cost for WBAN user p in training FL model j
$\zeta_{p,j}$, $\xi_{p,j}$	Unit cost for health data collection and unit privacy cost
$\mathrm{g}_{p,j}$	WBAN user p's computing resources for training FL model j
$\mathscr{w}_j$	Number of CPU cycles required to compute one data sample
$\mathrm{M}^{cmp}_{p,j}, \mathrm{X}^{cmp}_{p,j}, \mathscr{C}^{cmp}_{p,j}$	Computation time, energy, and cost for WBAN user p
$\varepsilon_p, \pi_{p,j}$	Effective capacitance of WBAN p's chip and unit energy cost
$\mathscr{P}_{p,j}$	Criticality of WBAN user's training data
$\mathscr{m}^{\mathrm{i}}_{p,j}$, $\mathscr{I}^{\mathrm{i}}_{p,j}$	Medical criticality and health severity index of data $\mathscr{A}^{\mathrm{i}}_{p,j}$
$\mathscr{Q}^{\mathrm{i}}_{low}$, $\mathscr{Q}^{\mathrm{i}}_{up}$	Lower and upper bound of health data $\mathscr{A}^{\mathrm{i}}_{p,j}$
$\mathscr{r}_{p,j}$	Data rate between WBAN user p and HSP for FL model j
$\mathscr{U}_j$, $\mathcal{B}_j$	Size of the local model and budget for FL model j
$\mathcal{T}_{p,j}$, $\mathcal{T}_j^{max}$	Total time for WBAN user p and deadline for FL model j
$\varsigma_{p,j}$	Positive parameter that depends on $\mathrm{F}_{p,j}(\mathbf{S}_{p,j})$
$\mathrm{M}^{trs}_{p,j}$, $\mathrm{X}^{trs}_{p,j}$, $\mathscr{C}^{trs}_{p,j}$	Transmission time, energy, and cost for WBAN p
$\mathbb{C}_{p,j}$, $\hat{\mathbb{C}}_{p,j}$	Total and reported costs of WBAN user p joining FL model j
$\mathfrak{a}_{p,j}$, $\mathrm{t}_{p,j}$	Positive and negative interactions between WBAN and HSP
$z_{p,j}, d_{p,j}, \mathfrak{u}_{p,j}$, $\mathrm{m}_{p,j}$	Belief, disbelief, uncertainty, and binary decision variable
$ß_1, ß_2, ß_3$, $\mathscr{L}_{p,j}$, $Ł_{p,j}$	Predefined weights, fact space, and conceptual space
$\mho_{p,j}, \mho'_{p,j}, \mho''_{p,j}$	Final, current, and historical reputations
$\Re_{p,j}$	Utility of WBAN p for the training of FL model j
$pay_{p,j}$	Payment received by WBAN user p for joining FL model j
$\mathbb{W}_{p,j}$	Valuation of WBAN user p's local model
$\mathscr{y}$	Conversion parameter for model performance into profit
$\mathscr{w}_1$, $\mathscr{w}_2$	Conversion coefficients for accuracy and reputation

Symbol	**Description**
$\mathcal{U}_{p,j}$	Utility of HSP for its FL model j due to WBAN user p
$\vartheta_{p,j}$	Cost per unit valuation for WBAN p in FL model j training
$\mathscr{N}_p$, $\mathscr{M}_j$	Candidate lists of FL model j and WBAN users p
$\mathscr{S}_j$	Selected set of WBAN users for FL model j

Abbreviations

Abbreviation	Description
WHO	World Health Organization
WBAN	Wireless Body Area Network
LD	Local Device
FC	Fog Computing
QoS	Quality of Service
FS	Fog Server
HSP	Health Service Provider
MC	Medical Center
ML	Machine Learning
UAV	Unmanned Aerial Vehicle
HAR	Human Activity Recognition
FL	Federated Learning
PRB	Physical Resource Block
HD	Healthcare Domain
RA	Resource Allocation
QNN	Quantized Neural Network
DP	Differential Privacy
HE	Homomorphic Encryption
PoW	Proof of Work
ADFL	Auction-Driven incentive mechanism for multiple FL
IoMT	Internet of Medical Things
IoT	Internet of Things
MEC	Mobile Edge Computing
WPT	Wireless Power Transfer
Non-IID	Non-Independent and Identically Distributed
CAA	Channel Allocation Algorithm
SSAA	Suboptimal Subchannel Assignment Algorithm

Abbreviation	**Description**
IIoT	Industrial Internet of Things
CS	Cloud Server
SINR	Signal-to-Interference-plus-Noise Ratio
BGV	Brakerski-Gentry-Vaikuntanathan
UMPM	Utility Maximization Patient Monitoring
ET	Execution Time
LP	Laptop
WS	Workstation
PS	Param Shivay
He-aaS	Healthcare-as-a-Service
ELPM	Energy and Latency-aware Patient Monitoring
BP	Blocking Pair
DaaS	Drones-as-a-Service
MBS	Macro Base Station
OFDMA	Orthogonal Frequency-Division Multiple Access
ECG	Electrocardiogram
EMG	Electromyography
RE	REward
MAC	Multiply-Accumulate
WMA	WBAN-Miner Association
DCRA	Deterministic Composite Residue Assumption
EFCS	Envy-Free Client Selection
CSPD	Client Selection and Payment Determination