Intelligent Node Fault Prediction and Route Optimization Mechanisms for IoT Networks

Thesis submitted in partial fulfillment
for the award of degree of

Doctor of Philosophy

By

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Dedicated to

Baba Vishwanath, Maa Annapurna,

Mother Nature and my beloved Husband

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Abbreviations

Abbreviation	**Description**
ABR	Area-Based Routing protocol
ACC	Average Clustering Coefficient
ADF	Auto Encoder Anomaly Detection with Fuzzy Framework
APL	Average Path Length
AR-VR	Augmented and Virtual Reality
BEEMH	Balanced and Energy Efficient Multi-Hop routing
CH	Cluster Head
CIoT	Consumer IoT
CNN	Convolutional Neural Network
CRPD	Clustering Routing Protocol for Dynamic WSNs
DBA	Distributed Bayesian Algorithm
DBSCAN	Density-Based Spatial Clustering
DDR	Dynamic Directional Routing
DDR	Dynamic Directional Routing protocol
DoA	Direction of Arrival
DRL	Deep Reinforcement Learning
E-FEERP	Enhanced Fuzzy Based Energy-Efficient Routing Protocol
EE	Energy-Efficiency
FN	False Negative

Abbreviation	**Description**
FP	False Positive
HMMs	Hidden Markov Models
IF	Isolation Forest
IoD	IoT Devices
IoT	Internet of Things
LEACH	Low Energy Adaptive Clustering Hierarchy
LMHR	Learning-based Multi-Hop data Routing
LOF	Local Outlier Factor
LPWAN	Low Power Wide Area Network
LSTM	Long Short-Term Memory
ML	Machine Learning
NM-LEACH	Novel Modified Low Energy Adaptive Clustering Hierarchy
PPO	Proximal Policy Optimization
PPP	Poisson Point Process
PSO	Particle Swarm Optimization
RF	Random Forest
RFID	Radio Frequency Identification
RL	Reinforcement Learning
RSSI	Received Signal Strength Indicator
SAC	Soft Actor-Critic
SD	Standard Deviation
SDR	Software-Defined Radio
Sec	Seconds
SEMI-GRU	Semi- Supervised Gated Recurrent Unit
SW-IoT	Small-World IoT
SWC	Small-World Characteristics

Abbreviation	**Description**
TN	True Negative
TP	True Positive
TS	Transmission Speed
UAVs	Unmanned Aerial Vehicles
V2X	Vehicle-to-Everything
WSN	Wireless Sensor Network

List of Symbols

Symbol	Description
$\mathcal{N}$, $\mathcal{M}$	set of N IoDs and set of M gateways, respectively
$\mathcal{L}$, $\mathcal{F}$	set of possible links and set of faulty nodes, respectively.
d_{jk}	distance between jth and kth IoDs
d_{max}	threshold distance between jth and kth IoDs
η_{jk}	incidence matrix element corresponding to node-pair j and k
$\mathcal{E}$, $\mathcal{H}$	set of residual energies for IoDs and set of a number of hop counts between IoD pairs
$\mathcal{Q}$, $\mathcal{V}$, and $\mathcal{P}$	set queue sizes over IoDs, set of transmission power levels from the IoDs, and set of flag bits for the IoDs
$P_k(f)$	flag bit predicting the fault status of kth IoD
L, W	length and width of the network
D^i_{jm}, E^i_{jm}, and T^i_{jm}	transmission delay occurred, data throughput observed, and energy consumed while transferring data from jth IoD to mth gateway at ith iteration of data transmission
p, ℓ	total number of data packets transmitted and length of the data packet

Symbol	**Description**
$E^i_{j,(res)}$	residual energy of the jth node at ith iteration
$\mathcal{I}$	interference observed over a node
∂	threshold value of residual energy
$D_{\text{tra.}}$, $D_{\text{pro.}}$	transmission and processing delays
$D_{\text{pkt.}}$, $D_{\text{que.}}$	packet and queuing delays
$D_{\text{con.}}$	delay due to conventional multihop data routing
R^m_i	total data received by mth gateway at ith iteration
R^j_i	total data generated by jth node at ith iteration
β^i_{jk}	data transferred from jth node to kth at ith iteration
S^i_k	state of a sensor node k at ith iteration
D_T, D_R	total data transmitted and total data received
T_D	message hold delay
A^i_k, A^z_k	data point A for kth node at ith and zth iteration
χ	reachability distance
$\Delta(A^i_k, K^i_k)$	distance between data point A and its Kth nearest data point
$\psi(A^i_k)$	local reachability density for data point A^i_j
$K_{(A^i_k)}$	K-neighbors of data point A
$\varphi(A^i_k)$	local outlier factor for data point A^i_k
α, γ	learning rate, and discount factor
s, s'	current and next state of the agent
a, $\mathcal{A}$	action taken to reach the next state, set of actions
$Q(s,a)$	Q-value associated with the action a at state s
ϵ	probability of exploitation
$\Re$	reward associated with selection of next state
$\Re_E$, $\Re_T$	reward factors corresponding to residual energy,

Symbol	Description
	data transmission delay
$\mathcal{L}_j$	set of virtual link for jth node
λ, μ	distribution parameter, mean of Poisson process
$E_{tx}(k,d)$	energy consumed by source IoD to transmit a k-bit data packet to receiver located at distance d
ε_e, ε_{fs}, and ε_{mp}	energy parameters used to model the energy consumption phenomena during switching on and off the transceiver, data transmission over free space, and multi-path, respectively
η_t^n	sum of normalized energy parameters for IoD n
θ, $R_{N\times N}$, $Q_{N\times N}$	data energy, reward matrix, Q-matrix
Q_{score}, $\zeta[\,]$	accumulated reward over training, IoD array for efficient routing
$\pi(s^n)$	optimal action taken in state s^n
$cs_t^n, pl_t^n, ls_t^n, br_t^n$	channel status, power level, latency, and bandwidth matrices for IoD n
MF_l, MF_m, MF_h	low, medium, and high membership functions
X_k, Y_k	X and Y coordinates of kth sensor node
N_{tr}, y_i	mini-batch size and Q-function target
γ, $\mathcal{H}_{\text{target}}$	discount factor and target entropy
a'_{i+1}	action sampled from policy at next state
S_{avg}	average size of a data packet