JSMCRP: Cross-Layer Architecture based Joint-Synchronous MAC and Routing Protocol for Wireless Sensor Network

Shruti Birur Viswanath†,
Thippeswamy M. Nagendrappa, and **Krishna Rao Venkatesh**, Non-members

ABSTRACT

The exponential rise in wireless technologies and allied applications has revitalized academia-industries to develop more efficient and economic routing solutions to meet Quality of Service (QoS) provision. Amongst the major wireless communication systems, Wireless Sensor Network (WSN) is the most sought after technology for defense surveillance, healthcare monitoring, industrial monitoring and control, civic and strategic infrastructure surveillance, etc. Additionally, the surge in Internet of Things (IoT) and Machine to Machine (M2M) communication systems have broadened the horizon for WSN communication. Considering it as motive in this paper, a highly robust "Cross-layer architecture based Joint-Synchronous MAC and Routing Protocol for WSN communication (JSMCRP)" has been developed. Being a cross-layer model, JSMCRP protocol, it employs Application Layer, Network Layer, MAC Layer, and PHY Layer to perform Network Adaptive MAC scheduling and make Dynamic Routing Decisions. JSMCRP employs Data Traffic Assessment, Prioritization, and Scheduling (DTAPS), Proactive Network Monitoring and Knowledge (PNMK), Dynamic Congestion Index Estimation (DCIE), Adaptive Link Quality, Dynamic Packet Injection Rate (DPIR), and Cumulative Rank Sensitive Routing Decision (CRSRD) to perform routing decisions. Additionally, exploiting dynamic network/node conditions, it performs Cognitive MAC scheduling to ensure QoS centric communication over an IEEE 802.15.4 protocol stack. JSMCRP exhibited higher packet delivery ratio (99 %), lower packet loss ratio (1 %), and low delay under varying network conditions, which makes it suitable for real-time communication in constrained mobile WSN conditions.

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The authors are with the Department of Computer Science and Engineering, Nitte Meenakshi Institute of Technology, Bangalore, India.

†Corresponding author: shruthi.bv@nmit.ac.in

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1. INTRODUCTION

Rising wireless communication demands have revitalized academia-industries to develop more efficient and robust routing solutions which retain QoS and allow energy-efficient data transmission. Amongst the major wireless communication systems, Wireless Sensor Network (WSN) has gained widespread attention because of its decentralized and infrastructure-less operating principles. On the other hand, being a cost-effective network solution, it has been applied to major localized communication purposes such as civic-surveillance, industrial monitoring and control, healthcare sector, tactical surveillance and tracking, defense sector, industrial set-up, and warehouse surveillance purposes [1–4]. Additionally, in the last few years WSNs have gained immense significance for IoT and M2M communication systems [1–6]. Undeniably, WSNs are vital to low-power, lossy network (LLN) communication systems, which have gained widespread attention for IoT ecosystems. Noticeably, most contemporary wireless communication systems demand QoS with mobility, which due to topological and node/network parameter variations, often undergoes change causing QoS violation. On the contrary, maintaining optimal QoS and energy-efficient routing is a must for WSN communication purposes, which require optimal routing decisions while ensuring high throughput, low latency, low end-to-end delay, low packet loss, and low re-transmission probability.

WSN, being a cooperatively communicating network, encompasses multiple distributed connected (sensor) nodes which can transfer data from the source to the destination node in single or multiple hops. On the other hand, the IoT ecosystems and M2M communication environments have been employing a mobility assisted transmission paradigm, which often undergoes topological variations and node/network parameter changes over time [7]. The inclusion of mobility with standard IEEE 802.15.4 based native WSN can yield a wide range of communication systems fulfilling contemporary demands. This motivates academia-industries to develop a robust routing model to incorporate mobility with WSN to achieve a QoS-centric, energy-efficient routing protocol. A number of research efforts have been made to enhance QoS provision and energy-efficiency in WSN. The majority of existing approaches either employ system level or PHY level information to perform routing decisions. Noticeably, system level information provides node statistics such as buffer availability and congestion, while PHY level provides information about bit error rate, residual energy, etc., to make routing decisions [1–4]. However, the dynamic nature of mobile-WSN or possible topological as well as node/network parameter changes can confine efficacy and QoS provision. Merely employing residual energy, or congestion information, or even sleep-awake scheduling cannot achieve an optimal solution. Recent literature [24] reveals that the strategic inclusion of both routing protocol as well as MAC, which primarily functions in the system layer, can enable optimal routing decisions [6–8]. MAC optimization or scheduling has always been vital to achieve reliable and QoS centric communication. However, the majority of the MAC optimization measures employ either sleep-awake scheduling or transmission delay scheduling [8]. In the last few years, authors have found that the integration of both MAC optimization and routing can enable more efficient solutions. Some research recommends employing node/network parameters such as congestion, delay or deadline time, resource availability, link quality information, etc. to make MAC enhancements that in conjunction with better PHY scheduling could achieve optimal routing solution for WSNs [8, 9]. Merely employing a single node or tweaking network parameters cannot ensure optimal routing towards QoS provision [2, 5–7] and hence collecting different node parameters from the varied layers of the WSN protocol stacks (Open System Interconnection (OSI) layers of IEEE standard 802.15.4) can help enable optimal routing. In major multihop communication systems, there is correlation and interdependence among various functions at the different layers of the protocol stack. Functions processed at the different layers of the protocol stack are inherently coupled because of the shared characteristics of the radio channel. Therefore, different functions that emphasize QoS delivery must not be considered distinctly when efficient solutions are needed. Due to the shared nature of the radio channel, there exists a strict interdependence amidst different functions at the different layers of the protocol stack. Therefore, correlating different functions and parameters at the different layers of the protocol stack can provide better strategic scheduling for QoS centric routing. In this paper, emphasis is made on exploiting different parameters from the different layers of the protocol stack to achieve QoS centric and reliable communication over mobile-WSNs. A cross-layer approach with the amalgamation of the different parameters from the varied OSI layers, called a cross-layer structure, can enable topology adaptive dynamic link estimation, congestion probability assessment, provide delay sensitive transmission [8] possibilities, lower resource consumption [9, 47, 48], etc. This can strengthen MAC to assist QoS centric communication [9].

Numerous existing MAC protocols apply sleep-awake scheduling to preserve energy [23, 40, 42]. A few employ handshaking concepts [39] to reduce data drop probability and reduce retransmission. However, these approaches are computationally complex and time-consuming and become more severe over large scale networks. This motivates us to design a Joint-Synchronous MAC and Routing Protocol (JSMCRP) for WSN communication. Functionally, JSMCRP embodies key features such as Data Traffic Assessment, Prioritization, and Scheduling (DTAPS) at application layer, Proactive Network Monitoring and Knowledge function (PNMK), Dynamic Congestion Index Estimation (DCIE), and the Cumulative Rank Sensitive Routing Decisions (CRSRD) at the network layer and Adaptive Link Quality, Packet Injection Rate and JSMCRP Cognitive MAC (JC-MAC) as the IEEE 802.15.4 MAC. The proposed JSMCRP has multiple contributions and novelties such as DTAPS assisted traffic classification, buffer allocation, prioritization, fair resource scheduling, deadline sensitive relaying decisions, multiple node parameter based relaying concept, and adaptive MAC scheduling. Such robustness enables our JSMCRP protocol to exhibit time-efficient and reliable data transmission over WSNs. Being a cross-layered structure, JSMCRP applies synchronized decision making or computation at the different layers, which enables it time-efficient as well as adaptive. On the other hand, the MAC model was applied as an adaptive scheduler which exploits node and/or network information dynamically to perform resource access and control. The functional approach allows JSMCRP to be referred to as Adaptive (Cognitive) MAC (JC-MAC) based Dynamic Routing Model to meet QoS demands. In summary, the keys contribution of this work can be stated as:

1. Network condition aware joint MAC and routing protocol for WSN under dynamic network condition.
2. Cross-layer information exchange model with Application layer, MAC layer, link layer or network layer, and PHY layer for adaptive MAC scheduling and routing decision.
3. QoS centric data traffic assessment, prioritization, and scheduling (DTAPS), proactive network monitoring and knowledge (PNMK) to support dynamic MAC scheduling and routing decisions, dynamic congestion index estimation (DCIE), adaptive link quality, packet injection rate sensitive MAC scheduling, and routing model for QoS com-

munication over WSN under dynamic topology.

4. Multi-parametric decision variable (here, cumulative rank sensitive routing decision (CRSRD)) based Cognitive MAC scheduling and routing over IEEE 802.15.4.

The remaining sections of this paper are divided as follows: Section 2 discusses the related work, which is followed by proposed system and implementation in Section 3. The results obtained are discussed in Section 4. Overall research conclusions are discussed in Section 5.

2. RELATED WORK

To enhance reliability and timely transmission, three different MAC models named Routing enhanced MAC (RMAC), Pipelined Routing enhanced MAC (PRMAC), and CLMAC were developed in [10]. In these MAC models, Packet Delivery Ratio (PDR) and delay information were used as scheduling decision variables. Contention Radio based MAC (CR-MAC) was proposed in [11], while an enhanced contention based synchronous protocol named Joint Routing and MAC (JRAM-MAC) was designed in [12]. Similarly, an integrated MAC and routing protocol was designed in [15], where JRAM-MAC was found to be efficient in terms of high PDR and energy. To achieve better performance and high energy-efficiency, CSMA-CDMA with multi-rate transmission was performed in [13, 14]. An adaptive operation cycle MAC was designed using an energy-quality balanced model with energy-aware routing decisions in wireless mesh devices [16]. A joint routing model with MAC and PHY layer was developed in [17] that resulted an Intelligent Hybrid (IH) MAC solution for WSN. However, it considered merely the shortest path to make routing decisions, which does not guarantee QoS under dynamic network topologies. Non-Destructive Interference MAC (NDI-MAC) was designed in [18] by exploiting non-destructive simultaneous transmissions into receiver-initiated protocols. It was found satisfactory under constrained network conditions with varying data dissemination. To achieve energy-efficiency and low latency, a Multi-Channel Pure Collective Aloha (MC-PCA) MAC protocol was developed in [18]. However, its complexity cannot be ignored. A Routing Enhanced MAC (RM-MAC) was developed in [20], where key focus was made on achieving timely data delivery. To achieve it, a cross-layer routing concept was recommended as a viable solution. However, the authors only used channel access time based on resource provision [20]. Directed Diffusion Routing Protocol (DDRP) with PDR sensitive MAC was developed in [21]. An enhanced concept named Receiver-Centric MAC (RC-MAC) was developed in [22], where varied traffic conditions were used to make transmission decisions. Harvested Energy Adaptive MAC (HEMAC) protocol was designed by applying a periodic listen and sleep concept with two frames, pioneer (PION) and explorer (EXP), to assist in making transmission decisions [23]. The use of latency or time-delay for path optimization was found to be a potential approach. With this motive, in [24] a joint routing and MAC scheduling model was developed for a Wireless Body Network (WBAN). Towards this goal, a cross layer routing concept was designed by amalgamating the MAC and PHY layers. Different hybrid MAC protocols including Hybrid Medium Access Control (H-MAC), Hybrid Sensor Medium Access Control (HSMAC), and Hybrid Medium Access Control (H-MAC) were developed in [25] to support Adaptive Demand Multipath Distance Vector (AOMDV) routing. Amongst those solutions, H-MAC based AOMDV was found to be energy-efficient. With similar motive, a lifetime-balancing MAC (LB-MAC) concept was developed in [26]. However, it could not address other aspects of the routing protocols for QoS communication.

An energy-aware EAMP-AIDC protocol was developed in [27] by means of adaptive individual duty cycle (AIDC) optimization that considers residual energy of nodes and data requirements to define each duty cycle dynamically [42]. Adaptive Energy Efficient and Rate Adaptation based Medium Access Control Routing Protocol (AEERA-MACRP) was developed in [28], which applied an adaptive energy strategy with a snooze/snoop duty cycle concept. Similarly, an Energy Aware Routing MAC Protocol (EARMP) was developed by varying duty cycles. However, inappropriate duty-cycling can make the MAC be constrained when handling dynamic traffic [30]. Location-Based RMAC (RL-MAC) applied location information to configure nodes with non-uniform CWmin (minimum contention window) to perform data forwarding over multiple hops [30]. However, distance information by itself cannot guarantee optimality over a dynamic network. Queuing delay and channel condition based MAC, iQueue-MAC was developed in [32], where CSMA/TDMA MAC was used together to perform transmission under burst traffic. Power-Control and Delay Aware Routing MAC protocol (PCDARM) was developed in [33] for multipath transmission, where resource allocation was performed in TDMA frames. Hop Extended Pipelined Routing MAC (HE-PRMAC) was developed to enable multi-hop transmission in a single duty cycle. The hop extended concept and RTR message assisted HE-PRMAC exhibited low latency and high throughput. Residual time was applied in [35] to design RD-MAC to achieve better traffic queue management. Depth-Base Routing MAC protocol (DBR-MAC) was developed in [36] that focused on delay resilient routing for an Underwater Acoustic Sensor Network (UASN). A cross-layer model was recently suggested in [37] by applying network and MAC layers. This approach applied a fitness function to make routing decisions, though its efficiency could be better with multiple network parameters. Additionally, the use of a handshake might introduce redundancy and delay. For multi-sink WSN (MS-WSN) a cross layer protocol was developed in [38]. However, it merely focused on buffer management to enhance performance. Similarly, resource reservation assisted MAC was developed in [39] for full-duplex WSN. Adaptive Geographic Any Cast (AGA-MAC) was proposed in [40] by solving a sleep-delay problem of asynchronous preamble-based MAC. PHY, MAC, and Network layers based cross-layer solution was developed in [41] to achieve energy-efficient routing while maintaining high SNR. Contention based Cross-Layer Synchronous MAC protocol (CROP-MAC) was designed in [42] using staggered sleep/wake scheduling, efficient synchronization, and routing layer information. Similarly, cross-layer information based multi-channel MAC protocol was developed for WSN. However, it could be more efficient with proactive network management ability. A cross-layer model was developed in [33] that dynamically switches the MAC behavior between TDMA and CSMA. A MAC-Aware Routing protocol for WSNs (MAR-WSN) was developed in [45] by applying cross-layer information. MAR-WSN employs two-hop information to make next-hop routing decisions. To achieve it, different parameters, including delay, energy consumption, and hop, were used. In [46], a tree-based routing protocol RAWMAC was developed.

3. SYSTEM MODEL

This section primarily discusses the overall proposed JSMCRC protocol and our implementation.

Noticeably, the native IEEE 802.15.4 protocol and even classical IEEE 802.11 (MANET) do not guarantee QoS over dynamic topology, though in IEEE 802.11e QoS provision is enabled. We hypothesize that the inclusion of dynamic node and network parameters from the different layers of the IEEE 802.15.4 protocol stack and employing them strategically to enhance MAC decision as well as eventual routing or relaying decision can help to achieve optimal performance. As a viable solution, retrieving dynamic information under varying node/network conditions is possible by employing PNMK, which can be considered as the key strength of the IEEE 802.11e protocol standard for QoS provision. Employing PNMK and updating it proactively as a synchronized approach with the details across the layers can enable optimization of both MAC as well as routing models. Unlike these classical routing protocols, our proposed cross-layer model intends to exploit the maximum possible dynamic node/network information to perform optimal routing, relaying and transmission scheduling. A novel and robust model named "Joint-Synchronous MAC and Routing Protocol (JSMCRP) for WSN communication (JSMCRP)" has been developed. JSMCRP is an amalgamation of both an enhanced routing approach and MAC optimization. Noticeably, the proposed JSMCRP routing protocol can also be characterised as a multi-parametric synchronous MAC which employs cross-layer information exchange over the IEEE 802.15.4 protocol stack to enable QoS centric communication. The proposed cross-layer modularity embodies dynamic network information from the Application, Network, MAC, and PHY layers. The key focus is made on exploiting system layer information to achieve optimal transmission efficiency over the IEEE 802.15.4 protocol stack. Additionally, employing upper layer information, MAC has been strengthened to enable dynamic link and packet velocity adaptive transmission. On the other hand, by employing congestion information and data traffic classification, the network layer obtains the best forwarding or relaying node to ensure negligible packet drops to achieve minimum energy consumption. Our JSMCRP protocol applies to the Application, Network, MAC, and PHY layers. The initial three are called the system layer. PHY signifies the physical layer of the OSI. Realizing the fact that in the majority of the real-time routing protocols there is data with different priorities or traffic rates, JSMCRP at first employs a novel DTAPS mechanism that classifies input traffic from the Application layers and updates PNMK. Subsequently it performs adaptive resource allocation and prioritization in conjunction with the MAC and network layers. Additionally, the Network layer enables JSMCRP to retrieve congestion level data to avoid a node, link, or path for reliable transmission. On the other hand, the MAC layer obtains packet velocity and adaptive link quality by employing packet deadline time, round trip time, and throughput information, respectively. The proposed MAC model enhances dynamic throughput performance by using a relaying node or neighbouring node and residual deadline time to schedule transmission and sleep-awake provision. This mechanism helps enabling optimal transmission scheduling to achieve QoS provision. On the other hand, employing the above stated parameters (i.e., dynamic link quality, packet velocity, congestion probability and hop-counts), our proposed JSMCRP protocol executes routing that eventually achieves maximum possible throughput, low packet loss, low retransmission, and higher source utilization. The schematic of the proposed JSMCRP protocol is given in Fig. 1.

A detailed discussion of the proposed routing protocol is provided next.

3.1 Application Layer

One of the key challenges in classical MAC and routing approaches is unawareness of the data or traffic types and its non-linearity. Traffic assessment and its classification can help the WSN network and

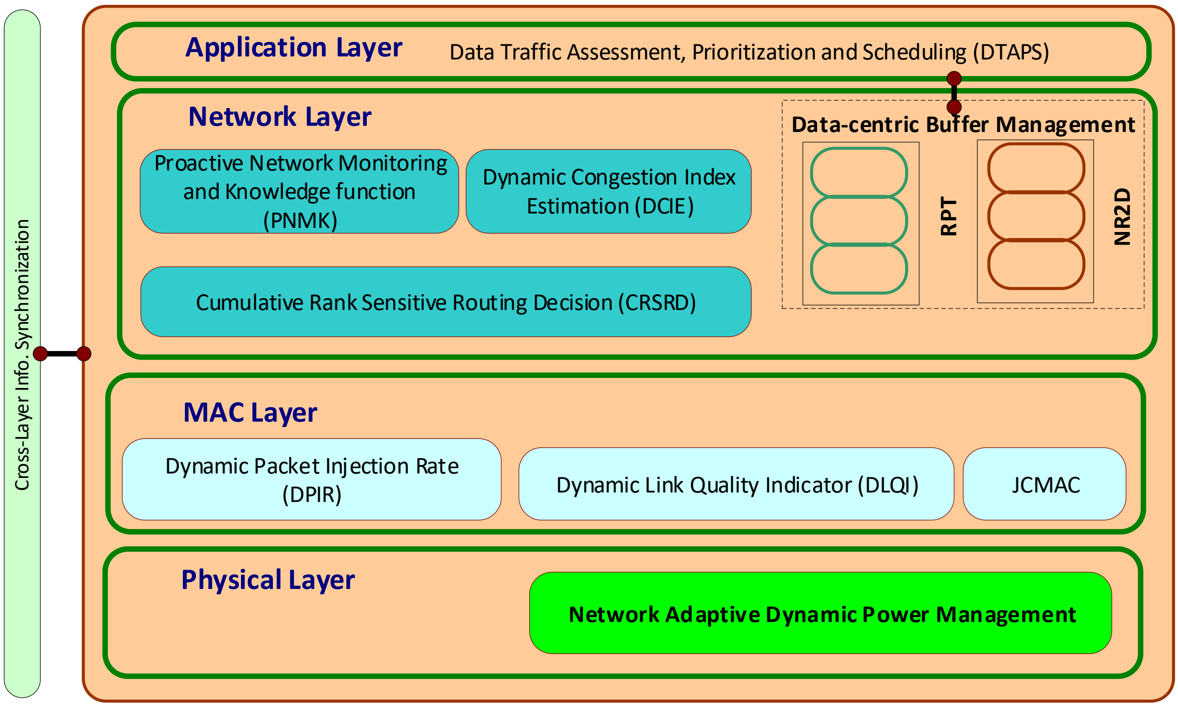

Fig.1: *Proposed JSMCRP protocol for QoS centric WSN systems.*

MAC layers make optimal transmission decisions. Being the top layer of the standard IEEE 802.15.4 protocol stack, the Application layer in JSMCRP performs DTAPS. The inclusion of DTAPS with JSMCRP protocol can enable adaptive prioritization and corresponding transmission decisions or resource scheduling. In DTAPS the input traffic at the Application layer is classified as Real Prioritized Traffic (RPT) and Non-Real Regular Data (NR2D). The level-of-significance (LoS) of traffic where RPT can be certain mission-critical information, while NR2D can be the data of inferior significance or certain log-details to be stored or entertainment data in multimedia communication. Observing these LoS, DTAPS at the Application layer intends to provide suitable resources or buffers to the RPT, while maintaining the maximum possible resources for the NR2D.

In WSN communication, especially for certain real-time communication, each packet used to have a certain deadline time to allow timely decisions by base stations or controllers. In such cases, it is mandatory to ensure timely data delivery within the defined packet's lifetime. In JSMCRP we considered this time-factor to assess priority of the data packets. Towards this objective, JSMCRP at first assigns a deadline time to each packet of 10 ms, while in adaptive prioritization it estimates the inter-node distance (between source and the sink) to identify the best relaying node and/or set of forwarding nodes to ensure packet delivery within the deadline time (i.e., 10 ms). Additionally, residual deadline time was obtained as the difference of initial timestamp T_{Tx} (at the time of transmission from source) and current time at i-th node, T_{iN}.

$$T_{Res} = T_{Tx} - T_{iN} \tag{1}$$

Thus, obtaining T_{Res} at each node, a forwarding node examines suitability of the neighboring nodes to know whether it can ensure delivery within available residual time-period T_{Res}. Now, to perform prioritization of each packet, we use a factor called the Time-Fraction T_{Fr}, which is obtained using Eq. (2).

$$T_{Fr} = \frac{T_{Res\_ij}}{d_i^j} \tag{2}$$

In Eq. (2), T_{Res_ij} states the residual deadline time, while the Euclidian distance in between the source i and the nearest sink j is given as d_i^j. Considering Eq. (2), it can be found that lower inter-node distance would increase T_{Fr} which is related to the transmission reliability, where higher time or residual time might have higher successful transmission probability. Therefore nodes with low inter-node distance would be considered in the neighbour table to make further routing decisions. JSMCRP obtains the time-of-arrival of each data packet and subtracts it from the total packet's deadline time, which as a result gives residual time $TRes$. Thus, each node obtains the residual time for a requesting node traffic and updates it in the DTAPS table, which is used by a requesting node to make transmission or relaying decisions.

Noticeably, in our JSMCRP approach, each node is assigned two-distinct buffers with same capacity, each dedicated for RPT and NR2D distinctly. WSN, being a resource constrained network with our proposed Dual-Distinct Buffer Model (DDBM), can ensure congestion avoidance during scheduling for different traffic types. In the majority of classical approaches, during congestion, all non-real-time traffic data is dumped or dropped to support reserving resources for real-time traffic (or RPD). Unlike such opportunistic routing protocols, a notable contribution of the proposed DTAPS model is its fair resource scheduling ability. During congestion, when a RPD buffer lacks sufficient resources, it borrows buffers from NR2D to accommodate continuous transmission. When both RPD and NR2D undergoe 100 % buffer utilization and RPD demands additional buffer space to accommodate real-time prioritized traffic, we drop a few packets (as per demand) from the NR2D buffer. Noticeably, in this approach, NR2D the buffer employs a First-In-First-Out (FIFO) resource management approach. Therefore, dropping a few recently added packets at NR2D does not violate QoS expectations significantly. In contrast, the majority of the classical MAC models or routing approaches drop all data of non-real-traffic to accommodate real-time traffic or RPD. In this manner (i.e., DTAPS), our proposed routing approach ensures optimal successful RPD data transmission, while achieving maximum possible fair transmission of the NR2D traffic. It achieves transmission reliability of both traffic types and hence makes JSMCRP robust to yield optimal performance.

3.2 Network Layer

At the network layer of the IEEE 802.15.4 protocol stack, we focus on retrieving key dynamic network information to make optimal routing decisions. In addition, congestion assessment is also performed at the network layer. In our proposed JSMCRP protocol we primarily execute two tasks: Proactive Network Monitoring and Knowledge (PNMK) and Dynamic Congestion Index Estimation (DCIE). The detailed discussion of the proposed mechanisms is given in the sub-sequent sections.

3.2.1 Proactive Network Monitoring and Knowledge (PNMK)

Noticeably, the majority of classical WSN protocols or MAC schedulers consider the WSN as static. However, the exponential rise in IoT and M2M communications that employ mobility in major operating environments shows dynamic topologies exist, along with corresponding node/network variations. Reactive network management based routing and MAC scheduling cannot yield better performance for a dynamic topology. In addition, the stale node or network information based routing can cause link outages, packet loss, data retransmission, delays and energy exhaustion, which can greatly violate the QoS provision aspect in WSNs. Hence, in this paper PNMK has been developed on top of the network layer. This enables dynamic or proactive node table management to help provide optimal MAC scheduling, routing, and relaying decisions. Our proposed PNMK model, being functional on the network layer, collects dynamic information about each node for its position, buffer availability, congestion, deadline time, link quality update, etc. These parameters all help in making optimal relaying and MAC scheduling decisions. Our proposed PNMK model keeps node tables updated by trans-receiving one-hop distance information from neighbouring nodes. In addition, since the PNMK model keeps updating the node tables, routing decisions in real-time retain optimal efficiency and successful transmission without imposing additional node discovery phases. It yields lower overall routing times using fewer resources as well as being energy-efficient. PNMK performs proactive network management by means of transmitting a beacon message to its neighbouring nodes. Transmitting PNMK beacon messages, each node obtains the one-hop distant node's information including NodeID, Node-Position, inter-node distance, packet delivery rate (i.e., the ratio of packet transmitted and received), link-quality, available buffer space, etc. To achieve it, we considered control packets of 512 bytes having three distinct sections containing NodeID, geographical position information, and dynamic node conditions or allied parameters. In major classical WSN protocols, packet sizes like 100–160 bits is maintained low to retain high throughput and reliable transmission [48]. However, it remains less efficient for high rate data transmission. It can be enhanced by enabling better scheduling and routing decisions, which motivates us to develop a robust solution like our proposed JSMCRP. We chose a packet size of 512 bytes. Being greedy in nature, WSN nodes might undergo contention or congestion scenarios. Therefore JSMCRP executes beaconing in such a manner that a connected node can multicast a beacon message only in conjunction with an offset timer. Here, the applied offset timer employs a classical uniform distribution concept where obtaining the transmission request from one node, the receiving node resets its timer and thus prohibits any possibility of unwanted beaconing or transmission from other nodes. It avoids congestion and reduces redundant transmission.

Let the deployed network encompass N cooperatively communicating nodes distributed across the network region. Consider A_j to be the one-hop distance neighboring node, while its best relay node or forwarding node is the BFN_i. Then, the proactive node table is updated as per Eq. (3).

$$\text{Table}_{\text{PNMK}} = \{BFN_i \in A_j | D_{SD} - D_{SF} \geq 0\} \quad (3)$$

In Eq. (3), the parameter D_{SD} signifies the distance in between the source and the nearest sink, while D_{SF} states the distance between source node and the nearest best relay or forwarding node. In this paper we estimated distance information using the Euclidean distance model. In dense network conditions, each node tries to consider the nearest forwarding node as a forwarding node to transmit its data, as it can enable high reliability and transmission rates. However, in a practical networking solution, a neighboring node with near-zero or zero inter-node distance should not be considered to be a candidate of the PNMK table. This is because it might be positioned near source location. Sending packets towards that destination merely adds additional hops, causing high computational overheads and latency. Additionally, as per Eq. (3), PNMK considers only those nodes which can ensure high residual time to achieve successful transmission.

3.2.2 Dynamic Congestion Index Estimation (DCIE)

In a significant amount of existing research, authors have considered congestion as decision parameter to make MAC scheduling or transmission (routing) decisions. However, congestion condition in static WSN and mobile-WSN, which is common in the contemporary application environment, are different. Unlike static WSN deployment, mobile based WSN or M2M communication often undergoes topological variations and hence increased probability of congestion due to multi-node traversal. Increased congestion often leads to data drop, and higher retransmission probability, which eventually degrades overall performance. Considering this fact, developing a dynamic congestion estimation model where congestion probability can vary over an operating period is a must for a QoS centric WSN. Unlike classical congestion detection approaches, in our proposed JSMCRP protocol, a time-sensitive and buffer assessment based approach which works with a dynamic network topology is designed for dynamic congestion estimation. At first it exploits the buffer information, such as the maximum buffer capacity of each node, resources consumed or buffer availability, round-trip time (RTT) information, etc. to perform congestion estimation. Subsequently it examines overall congestion on a node caused because of all neighboring or connected (forwarding) nodes.

JSMCRP obtains maximum buffer capacity and current buffer availability of a node from the PNMK table, which helps each node to identify the neighboring node undergoing congestion. JSMCRP estimates the congestion degree of each node, while assuming that a node can have payload(s) from multiple neighboring nodes as well. Mathematically,

$$CD_F = \frac{CD_{RPD} + CD_{NR2D}}{CD_{RPD\_Max} + CD_{NR2D\_Max}} \quad (4)$$

$$CD_r = \sum_{i=1}^{N} CD_{Fi} \quad (5)$$

In Eq. (4), the buffer available for RPD traffic is given by CD_{RPD}, while the buffer available for NR2D traffic at a node is CD_{NR2D}. On the other hand, the maximum buffer assigned for NR2D is CD_{NR2D_Max}, while the same for TPD is CD_{RPD_Max}. CD_F presents the congestion on a node, while the total congestion caused due to other connected nodes (say, N) is CD_r in Eq. (5). Noticeably, these parameters are dynamically updated for PNMK dynamically. PNMK is used by nodes to make adaptive routing decisions and to do MAC scheduling. Our proposed JSMCRP protocol which addresses both MAC scheduling as well as routing decisions employs CD_r information of each participating node (say, neighboring node) to assist in choosing the best relaying node for data transmission. In other words, when transmitting packets, a forwarding node will consider its neighbour as a relay node or best forwarding node only when it possesses low CD_r. JSMCRP applies CD_r as one of the decision variables for relaying decisions as well as MAC scheduling. The use of congestion degree information helps each node to assess neighbouring nodes for its suitability or ability to forward its data without causing any packet drop and/or delay. JSMCRP-MAC also applies congestion degree information to control sleep-awake scheduling for energy-efficient transmission.

3.3 MAC Layer

Undeniably, the MAC layer (the data layer) plays a decisive role towards enabling reliable transmission. However, in major existing research or MAC models, authors have either focussed on “Energy-centric sleep-awake scheduling” or link or congestion sensitive transmission decisions [11, 12, 31]. However, in contemporary WSN communication environment, it is mandatory to maintain energy-efficiency, QoS, as well as deadline sensitive transmission. Considering this fact, in this paper we focused on deriving a “Deadline-Sensitive Transmission Decision Variable (DSTDV)” which can exploit node/network information from both the system and the PHY layers to perform MAC scheduling. To meet this objective, the JSMCRP protocol derives two DSTDVs: Dynamic Packet Injection Rate (DPIR) and Dynamic Link Quality Index (DLQI). A snippet of the MAC functions is given as follows.

3.3.1 Dynamic Packet Injection Rate (DPIR)

Considering we are targeting a QoS-centric and reliable routing solution, the JSMCRP protocol intends to ensure that the packets or data reaches the destination within the deadline time while maintaining a "no-compromise" policy with successful data delivery. Major existing MAC protocols intend to achieve either energy-efficiency or reliable transmission by applying network parameters such as congestion free transmission scheduling or sufficient link condition based routing. However, in real-time communication, even in a congestion free route and with sufficient link conditions, a node cannot guarantee timely data delivery within a deadline time because it does not schedule transmission by considering a packet's deadline time. There can be nodes with sufficient link quality and buffer availability that still can take more buffer time, also called a holding-period, to transmit data. This holding period can even be more than the deadline period. As a result, this can make real-time data stale and hence can cause many hazardous consequences, especially for industrial monitoring and control, defence, and the healthcare sectors. Considering this fact, in this paper our proposed JSMCRP protocol introduces a new variable, or DSTDV, which employs time and inter-node distance information to examine the transmission rate of each participating node to enable transmission scheduling in such a manner that the relay node ensures delivery of data within the deadline time without compromising QoS and reliability. Our JSMCRP protocol applies the DPIR of each node DPIR_i for transmission scheduling. DPIR_i is also applied to perform relaying decisions. The detailed discussion of the proposed DPIR mechanism is given next.

In the DPIR model, packet velocity signifies the speed with which a particular node (say, i) can transmit targeted data to the destination or the sink node. A node with high DPIR can be more suitable to transmit data. In this relation, our JSMCRP protocol employs inter-node distance, D^i_{IND} (or the multi-hop distance from the source node to the destination) and round trip time information. We obtained the Euclidean distance between the source and the sink node with Eq. (6).

$$D^i_{IND} = D^i_{Eucl\_SD} - D^i_{Eucl\_ND} \tag{6}$$

In Eq. (6), $D^i_{Eucl\_SD}$ specifies the Euclidean distance between the source node and the destination node, while the distance between source and the nearest destination is $D^i_{Eucl\_ND}$.

Applying a generic speed equation, i.e., the ratio of distance and time, we obtained DPIR. For a transmitting node, let i be the neighboring node then we obtain the distance between the neighbouring or relay node and the sink. In some of the existing work, packet velocity is obtained as the "ratio of distance between source and destination, and round trip time", which seems inefficient and questionable especially when the transmission has to be done in multi-hop transmission manner. In practical multi-hop transmission, each participating node can have different transmission ability and transmission velocity and therefore we have considered "Summation and Averaging Concept" (SAC) to obtain DPIR. To transmit packet i to j, which are the source and the destination nodes, respectively, there can be 4 hops, where four distinct (participating) nodes can have different transmission abilities which primarily depend on the oscillation capacity, residual energy, etc. In this case, SAC applies Eq. (7) to obtain total traversal time (TTT).

$$T_{tot} = \sum_{i=1}^{j} \left(\Delta t_{i\to(i+1)}\right) + \sum_{j=1}^{i} \left(\Delta t_{j\to(j-1)}\right) \tag{7}$$

After obtaining T_{tot}, we averaged it to obtain Average Round Trip Time (ARTT). T_{tot} is considered the time-difference between transmitting and receiving ACK. We obtained ARTT_i for the i-th source node with Eq. (8).

$$\mathrm{ARTT}_i = \frac{T_{tot}}{2} \tag{8}$$

For n-hop transmission we obtained ARTT_n with Eq. (9).

$$\mathrm{ARTT}_n = \frac{T_{tot}}{N} \tag{9}$$

ARTT_n can also be obtained using Eq. (10).

$$\mathrm{ARTT}_n = \frac{\sum_{i=0}^{N} T^i_{D\_ACK} - T^i_{S\_ACK}}{N} \tag{10}$$

In Eq. (10), $T^i_{D\_ACK}$ signifies the time when a transmitter received ACK as acknowledgment, while $T^i_{S\_ACK}$ stated the time or instant (say, time stamp) when the node i transmitted the packet towards the destination. Here, N states the number of nodes traversed between the source and the sink node. Now, applying distance information D^i_{IND} in Eq. (6) and $ARTT_n$ in Eq. (10), we have obtained the speed of transmission by the i-th node with Eq. (11).

$$S_{TR\_i} = \frac{D^i_{IND}}{\mathrm{ARTT}_n} \tag{11}$$

Although the model derived in Eq. (11) gives mathematical expression for the possible transmission speed by a node, the transmission is in radio form in open-air space, so its normalization is a must. Here, normalization signifies the transmission rate or injection rate by a node at certain definite power level under an open-air environment. Eventually, the speed with which a node can transmit can be obtained using Eq. (12).

$$\mathrm{DPIR}_i = \frac{S_{TR\_i}}{S_{\mathrm{RadioOpenAir}}} \tag{12}$$

In Eq. (12), $S_{\text{RadioOpenAir}}$ states the speed of radio signal in open air. Here we set $S_{\text{RadioOpenAir}}$ to 3×10^8 m/s.

3.3.2 Dynamic Link Quality Indicator (DLQI)

In addition to the DPIR provision, our proposed JSMCRP protocol examines the dynamic link quality of each node for transmission scheduling. Undeniably, WSNs under mobility might undergo continuous change in topology, inter-node distance, Received Signal Strength Indicator (RSSI), Signal to Noise Ratio (SNR), Bit Error Rate (BER), and throughput performance. Variations in link-quality might directly impact link-sustainability, and in the case of high link-fluctuation, it might cause premature link-outage, causing data drops and retransmission. This eventually can force the network to undergo retransmission and hence delay, increased resource consumption, lifetime depletion, etc. In such cases, assessing link quality dynamically and deciding resource access control accordingly can be of utmost significance. With this motive, our proposed system incorporates a novel DLQI. The JSMCRP protocol ensures that transmitting data or packets can be more suitable with high DLQI and hence we employ the Window Mean Exponentially Weighted Moving Average algorithm to estimate the link-quality of each node dynamically. As stated above, the link-quality of a node can be characterised in terms of RSSI, SNR, throughput, BER, etc. Considering this fact, in this paper we used throughput information Eq. (13) to estimate DLQI. Eq. (14) can also be used for a viable and QoS centric transmission scheduling.

$$\text{PDR}_{ij} = \frac{P_{Rx}}{P_{Tx}} \tag{13}$$

In Eq. (13), P_{Rx} states the total number of packets received, while the variable P_{Tx} states the total number of packets transmitted by the i-th node to the neighbouring j-th node. We used Eq. (14) to estimate DLQI for each neighboring node in the vicinity to allow optimal routing and transmission scheduling.

$$\beta_{DLQI} = \mu * \beta_{DLQI} + (1 - \alpha) * (\text{PDR}_{ij}) \tag{14}$$

In Eq. (14), β_{DLQI} states the DLQI of a node, while μ signifies a network coefficient which varies in the range of 0 to 1. In addition to the DLQI condition presented in (14), we can also apply the bit error probability (BEP) of a link to perform transmission scheduling or resource access control. To achieve that, the maximum probabilistic approach α^n can be applied. For total transmission power $\sum_{tx}^{n}$, the maximum likelihood α^n can be obtained with Eq. (15).

$$\alpha^n = \alpha\left(c^n, \sum_{tx}^{n}, \text{PDR}^n\right) \tag{15}$$

$$\sum_{tx}^{n} = \varepsilon_{Tx}\left(c^n, \alpha^n, \text{PDR}^n\right) \tag{16}$$

In Eqs. (15) and (16), the variable PDR^n states the throughput estimated for n-th time interval, or ARTT, and the corresponding transmission power is given as ε_{Tx}. With this model, the packet loss rate between two nodes with N packets can be obtained using BEP with Eq. (17).

$$\text{BEP}^n = 1 - (1 - \alpha^n)^N \tag{17}$$

3.3.3 JSMCRP Cog-MAC: JCMAC

As already stated, this research contributes a joint routing and MAC scheduling paradigm to achieve QoS provision, and hence in addition to the CRF assisted routing solution, we have designed a MAC scheduling concept which exploits node/network parameters to make cognitive (scheduling) decisions. The proposed MAC model employs different parameters from the PNMK table to perform adaptive MAC scheduling. Considering the backward compatibility of the proposed WSN model, we have retained the TDMA-MAC feature within JCMAC. In this approach, each connected node has been allotted its autonomously decisive or own time slot on the basis of the information available in PNMK and allied neighboring information. Here, each node listens to the beacon signal and waits for ACK to collect and update it in PNMK for time slot allocation and synchronization purposes. During initialization, we applied multiple constraints, or a CRF-based mechanism, to perform relaying decisions or best forwarding node selection (using the JSMCRP protocol). Once obtaining the best forwarding node or the best relay node, the nodes select a time-slot arbitrarily to transmit data towards the destination. Noticeably, unlike classical contention based MAC scheduling or channel access [15–17], we applied multiple parameters. This makes JSMCRP more robust, cognitive, and scalable for mobile-WSNs. As stated, we do this using maximum link quality DLQI, high packet velocity or injection rate DPIR, and low congestion probability DCI. This information is used by each node to decide resource access in each time-slot. In addition, to avoid any congestion, we applied an offset timer (discussed in PNMK) in conjunction with an Adaptive Multi Time-Slot Allocation (AMTSA) model, which significantly lowers congestion probability amongst the neighboring nodes and ensures QoS centric transmission over WSN. Additionally, the MAC has been designed as a distributed resource scheduler. It assigns a time-slot to the node only when it demands to transmit data. Additionally, respective data priority is also considered to assign the time-slot adaptively. In this approach, the number of time-slots is split based on data or frame-priority. Hence, once one data packet or frame is transmitted, the node contents iteratively send packets to gain a time-slot for further transmission. This process continues until all packets of a node are transmitted successfully. In this manner, each connected sensor node in WSN gets a fair opportunity to transmit its data without causing contention or packet drops. Furthermore, to preserve energy-efficiency of the proposed model, we designed the MAC layer so that a node switches to sleep mode when it does not have data to transmit or receive. Each sensor node wakes up at the initiation of a time-slot to listen for a beacon message from its neighbor. Once identifying any request, it sends ACK, and then JSMCRP comes into the picture to perform further transmission tasks. Noticeably, in our proposed model, we exploited beacon messages as a synchronization-tool. This helps exchanging information across the network to enabled PNMK formation and further routing decisions. Unlike the classical TDMA model, our proposed JCMAC concept ensures better resource allocation as per traffic demands. On the other hand, DTAPS provision also enables optimal resource allocation without causing data drops or resource wastage. In this manner, our proposed model achieves optimal performance to meet QoS provision requirements over WSNs by enabling time-efficient (deadline sensitive, and delay-resilient) transmission while ensuring higher resource utilization for both RPT and NR2D traffic. JCMAC can also monitor the use pattern of each node dynamically over each assigned time-slot, which helps making predictive or stochastic resource allocation. As an adaptive solution, for high traffic demands, it can assign more time-slots cognitively, while for low-traffic and less behavior it can reduce the frequency of the time-slots. This achieves reliable and resource efficient transmission.

The above section discussed MAC formulation to perform reliable data transmission. In our proposed routing as resource access control, we have applied an adaptive CSMA MAC model. The detailed discussion of the proposed adaptive MAC model is given in the next section.

3.3.4 Cumulative Rank Sensitive Routing Decision (CRSRD)

Being a joint routing-MAC scheduling approach, our proposed JSMCRP protocol at first performs multi-constraint routing decisions, followed by MAC scheduling. Unlike classical single parameter based routing decision or best forwarding node selection (also called relay decision) methods, the JSMCRP protocol applies multiple node/network parameters to decide the best forwarding node to perform reliable and QoS centric communication. We have derived a Cumulative Rank Factor (CRF) based on the different parameters obtained from the PNMK table. These parameters are:

- Dynamic Congestion Index Estimation (DCIE) - CD_r
- Dynamic Packet Injection Rate (DPIR) - DPIR_i
- Dynamic Link Quality Indicator (DLQI) - β_{DLQI}.

Thus, employing the above stated three key (dynamic) node parameters, our proposed JSMCRP protocol assesses each neighbouring node and examines its suitability as the best forwarding node to ensure reliable QoS-centric communication. Applying these node parameters, we obtain a Rank factor called the Cumulative Rank Factor for each node (i.e., $\mathrm{CRF}_{i\in N}$), where N states the set of neighboring node or on-hop distant node using Eq. (18).

$$\mathrm{CRF}_{i\in N} = \omega_1 * CD_r + \omega_2 * \mathrm{DPIR}_i + \omega_3 * \beta_{DLQI} \quad (18)$$

In Eq. (18), the variable ω signifies a weight component which can be assigned based on network conditions and/or preferences. The value of weight parameter ω_i ranges from 0 to 1, and follows Eq. (19) as a condition.

$$\sum_{i=1}^{3} \omega_i = 1 \quad (19)$$

A network demanding higher link quality can have ω_3 higher than ω_2 and/or ω_1. Similarly, a network demanding high congestion resilience can have a higher weight value ω_1 than the other weight components. Considering QoS centric network conditions, in this paper we assigned 0.3, 0.3 and 0.4 to ω_1, ω_2, and ω_3, respectively.

The detailed discussion about the reason behind our choices for ω_1, ω_2, and ω_3 is given next.

In classical routing models, authors have merely applied single node and/or network parameters such as residual link quality, congestion, packet velocity or probable rate of transmission, and residual energy to perform best forwarding node (BFN) (or best forwarding path (BFP)) selection. In this paper, the key emphasis was made on applying multiple node/network parameters to perform BFN or BFP that as a result could achieve QoS centric communication. In synch with the proposed model, we applied packet velocity, adaptive link quality, and congestion probability as the three node/network parameters to perform BFN and/or BFP selection.

Unlike in a typical single parameter-based model, we applied these three parameters together to formulate BFN selection. The selection criteria could be obtained with Eq. (20).

$$\begin{aligned}\mathrm{BFN_{SelCriteria}} = &\ \text{A. Congestion} \\ &+ \text{B. Packet velocity (dynamic packet injection rate)} \\ &+ \text{C. Dynamic link quality}\end{aligned} \tag{20}$$

Since these three parameters are different entities characterizing different motives or network conditions, amalgamating them together requires using certain multipliers which could provide a fair or targeted preference. In other words, based on the network conditions, the preference can be given towards the above stated multipliers or the weight parameters ω_1, ω_2, and ω_3. In synch with Eqs. (18) and (19), we defined above BFN model as Eq. (18).

Since, the maximum value of these weight parameters is supposed to be 1, we must assign values to them in such a manner that we can achieve the QoS goal. Now, recalling the fact that ensuring QoS demands maintaining high-throughput, low delay, and high reliability, these parameters are required to be assigned in fair manner.

In conjunction with the QoS demand and allied provisioning, these weight parameters can be selected based on the network conditions and corresponding network application demands.

Case-1 In practice in a the real-world application environment, there can be a network condition where congestion probability can be higher. For example, in mobile networks where different nodes can transmit respective data arbitrarily causing congestion network. Such an impulsive or transient increase in congestion might cause packet drops, which eventually would force the network to undergo high-retransmission and delay. To avoid it, the respective weight parameter (here, ω_1) must be selected in such a manner that it could select only a node with minimum congestion probability. In other words, the CRF must be estimated in reference to cumulative congestion probability. Considering this fact, we assigned 0.3 as the weight parameter related to the CD_r.

Noticeably, in case one network demands addressing merely congestion probability and we know that the other parameters (i.e., packet injection rate and link quality) are not critical, the value of ω_1 can be higher while maintaining the other parameters as low as we prefer or even set them to zero. In other words, if a network does not demand addressing link-quality or injection rate parameters for forwarding path selection, ω_2 and ω_3 can be zero. By doing so, Eq. (18) can be reframed as Eq. (21)

$$\begin{aligned}\mathrm{CRF}_{i\in N} &= \omega_1 * CD_r + 0 * \mathrm{DPIR}_i + 0 * \beta_{DLQI} \\ \mathrm{CRF}_{i\in N} &= \omega_1 * CD_r\end{aligned} \tag{21}$$

Table 1: *Weight parameter selection.*

Network parameter	Significance towards QoS provision, especially under mobile topology	Weight assigned
β_{DLQI}	High	$\omega_1 = 0.4$
CD_r	Moderate	$\omega_2 = 0.3$
$DPIR_i$	Moderate	$\omega_3 = 0.3$
		Sum of weights = 1

The above derived function signifies that the only criteria is the congestion detection probability (with $\omega_1 = 1$, as per Eq. (19)). Since in this paper the emphasis was placed on applying a multiple network or node parameters-based approach for BFN selection, we applied a "self-consciousness" based approach where we gave equal significance to congestion probability as well as packet injection rate.

Case-2 There can be a network demand (towards QoS delivery) where the data transmitting should be done within a defined timeline (say, deadline). In this case, a node with a higher transmission rate must be taken into consideration for BFP selection or formation. In this case, the fair selection of ω_2 can be of great significance. To ensure QoS provision, especially when fast data rate transmission is a must, maintaining a high weight value for ω_2 is a must.

Case-3 In major at-hand applications there can be dynamic variation in link quality, and therefore an application specific scenario where such dynamism is required needs to be addressed. In that case, assigning a higher value to ω_3 is a must. Since, our proposed model applied mobility features, there can be a higher probability of link-changes and therefore we assigned relatively more weight value towards DLQI.

In summary, considering major at hand applications or contemporary network demands (especially towards QoS provision), we applied a criterion which could employ multiple parameters to decide suitability of a node to become BFN or eventual BFP participant. Since we have applied multiple parameters whose "cumulative affect" was required to be considered for BFN selection, we assigned weight parameters. However, realizing the considered network condition where due to mobility link-quality was required to be considered the most important, followed by rate of transmission (i.e., higher injection rate) and affordable congestion, we gave higher preference to β_{DLQI} followed by CD_r and DPIR_i whose corresponding weights were assigned as 0.4, 03 and 0.3 respectively as in Table 1.

For real-world applications, assessing at-hand network conditions (by examining congestion probability, node mobility and resulting outage probability, and rate of transmission or delay sensitive communication), the values of the weight parameters (ω_1, ω_2, and ω_3) can be selected.

Thus, by obtaining the cost factor $\mathrm{CRF}_{i\in N}$ of each neighbouring node, the JSMCRP protocol identifies the BFN to make forwarding path and routing decisions using Eq. (22).

$$\mathrm{BFN}_{i\in N} = \max\left(\mathrm{CRF}_{i\in N}\right) \tag{22}$$

In JSMCRP, a node with the maximum $\mathrm{CRF}_{i\in N}$ is considered as the BFN or the relay node to perform data transmission.

4. RESULTS AND DISCUSSION

Considering the rising popularity of WSN applications, especially in the IoT ecosystem and for M2M communication purposes which often employ mobility, this paper focused on designing a robust networking solution which could take care of both dynamic network changes and still fulfill QoS demands. In fact, the majority of classical WSNs are considered to be static in nature. They typically do not undergo any topological variations, though they also undergo link outages due to node deaths. In contrast, a mobility based network can often undergo topological variations causing inter-node distance variation, higher link-outage probability, more congestion and/or contention, etc. These factors often make QoS vulnerable, thus impacting overall network performance. On the other hand, native WSNs which are based on the IEEE 802.15.4 standard do not guarantee QoS. Few provisions are available in IEEE 802.11e protocol standard. Under such limitations and in constrained conditions, the exponential surge in mobile WSN adoption, especially in IoT ecosystems and for other M2M communications, it becomes necessary to design a robust routing model to guarantee QoS provision as well as energy efficiency. Realizing the fact that MAC scheduling and access control also have a decisive impact on the performance of a routing protocol, developing robust and "network-adaptive" MAC scheduling is of utmost significance. Enabling "Network Adaptive MAC Scheduling" and "Network Adaptive Routing Decisions" requires having dynamic network and node information, which in turn requires a proactive network management strategy. Considering these as motives, we developed a highly robust JSMCRP for WSN communication (JSMCRP). The JSMCRP protocol embodies adaptive routing decisions as well as adaptive or cognitive MAC scheduling. Being a cross layer approach it manages the Application, Network, MAC, and PHY layers. Here, our predominant goal was to prioritize input traffic based on its nature, deadline time, etc. so that further routing, buffer allocation, and MAC resource access could be controlled. In synch with the real-time communication, our DTAPS model classified data traffic as either RPT or NR2D, though the duo were implemented with autonomous buffer provision to avoid any contention probability and packet loss. On the other hand, the network layer performed highly significant tasks such as PNMK, DCIE, and CRSRD. In the classical IEEE 802.14.5 protocol stack, reactive node management is performed. To cope with the dynamic network condition, we instead employed a robust PNMK model which collected node as well as network parameters dynamically to help nodes find optimal CRSRD for QoS centric routing decision. In addition, PNMK helped JCMAC to perform cognitive or adaptive MAC scheduling to meet QoS demands. On the other hand, dual-buffer based resource scheduling also enabled significant (QoS-oriented) resource allocation without imposing any contention or congestion. To perform "Network Adaptive Routing Decisions" JSMCRP applied cross-layer information from PNMK such as the Dynamic Congestion Index (DCI) (using DCIE), DPIR, and DLQI values, which allowed calculating a cost factor to perform optimal forwarding node selection and make routing/relaying decisions. Thus, the proposed routing protocol ensures that the forwarding node(s) across the relaying path can ensure timely, congestion-free, and reliable (packet) transmission to meet QoS demands. To enable adaptive MAC scheduling, our proposed JCMAC model employs PNMK information to perform dynamic resource management and scheduling. In this paper, the predominant emphasis was made on achieving QoS centric routing by means of the previously mentioned "Network Adaptive MAC Scheduling" and "Network Adaptive Routing Decisions". PHY switching, or switching control, is not addressed in this work. To retain backward compatibility, our proposed protocol JSMCRP protocol was applied on top of the native WSN protocol stack IEEE 802.15.4. The overall research model was developed using MATLAB, and corresponding performance was examined in terms of throughput, packet loss and delay. Some of the key simulation parameters and their respective configuration parameters are given in Table 2.

For network deployment, we must support a real-time communicating environment, we considered each node to be moving randomly across the strategically deployed network region. By strategically deployed network, we mean an environment where the overall network region can be visualized as a network with randomly moving mobile nodes with certain targeted sinks deployed at certain defined locations to receive transmitted data. Since mobility was considered to be circular in nature, 6 distinct sinks were deployed at angles of 60°, 120°, 160°, 240°, 300°, and 360° in reference to the network center. This positioning in polar form helped retrieving distance when computing polar to cartesian conversion. This distance information was updated in PNMK, which was later used for packet injection rate, inter-node

Table 2: *JSMCRP simulation environment.*

Parameter	Specification
Protocol	JSMCRP
Physical	IEEE 802.15.4PHY
MAC	JCMAC on top of IEEE 802.15.4MAC
Sink Nodes	6
Link-layer	TDMA/CSMA-CA
Packet Size	512 bits
Range	50, 100 meters
Network Area	$100 \times 100\,\mathrm{m}^2$
Deadline period	10 ms (each packet)
Mobility-Pattern	Circular
Node velocity	Time-varying/Non-linear
CRSRD Weights	$\omega_1 = 0.3$, $\omega_2 = 0.3$, $\omega_3 = 0.4$
Simulation Time (s)	800, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000
Mobile Nodes	10, 20, 30, 40, 50, 60
Payload	250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000

distance estimation, etc. The detailed discussion of the performance assessment by our proposed JSMCRP is given in the subsequent discussion.

To examine the robustness of JSMCRP, we assessed its efficacy in terms of two distinct paradigms, qualitative assessment and quantitative assessment. In qualitative assessment, we have considered design and the respective significance of performing routing or transmission over WSNs. Quantitative assessment exhibits simulation based comparison to assess whether JSMCRP outperforms existing approaches or not.

4.1 Qualitative Assessment

To perform qualitative assessment, we used secondary sources where different state of the art techniques developed for WSN routing and MAC scheduling were examined in reference to our goal. Although there is a significant amount of research about MAC protocol use in WSN, we considered only a few recent works employing multiple network parameters or a cross layer architecture. Table 3 presents a snippet of some of the existing approaches for implementing a MAC protocol in WSN.

Table 3 shows different existing approaches and their associated methods. It can easily be asserted that the proposed JSMCRP protocol uses more network parameters (i.e., PDR, Link quality, Velocity, Congestion, Delay, Deadline time or the residual time, and buffer conditions) to perform routing as well as to make MAC decisions. In fact, JSMCRP inherits the robustness of both MAC based routing as well as multi-parameter based adaptive routing, which makes it more robust and yield better performance. The consideration of cross layer structure enables optimal information exchange across the OSI layers, which makes routing decisions more effective. On the other hand, unlike in reactive routing approaches, the use of dynamic network parameters makes overall MAC as well as routing decision adaptive and cognitive. The overall processes is more calibrated and optimistically designed to serve QoS provision in mobile WSN. The provision of joint synchronization routing and MAC scheduling makes overall process more robust to yield reliability and enhance QoS. The majority of existing approaches have applied either one or two parameters to perform routing and MAC scheduling, and therefore those systems lack robustness and fail to yield optimal performance. For example, the consideration of link quality as a routing variable can make transmission reliable. However, lack of velocity consideration might make data under consideration stale, thus impacting overall performance. Similarly, the use of congestion for MAC scheduling can enable congestion-free transmission for energy efficiency. However, lack of dynamic link assessment can cause pre-mature link-outages causing packet drops and resulting in delay and energy-exhaustion. These factors affirm that our proposed JSMCRP protocol, which is a strategic amalgamation of adaptive routing protocol and cognitive MAC, makes overall WSN communication more efficient, robust and reliable to meet QoS and energy-demands. Our proposed JSMCRP outperforms other state-of-art techniques because of its multi-constrain consideration and adaptive routing and MAC scheduling (cognitive) ability.

4.2 Quantitative Assessment

For quantitative assessment and performance evaluation of the proposed JSMCRP protocol, we need to consider a reference model which deploys both cross layer structure as well as a joint routing and MAC scheme for WSN. Performing an extensive literature survey over the last few years, we found an approach called Enhanced Energy-Aware Topology Design for Wireless Body Area Networks (EEAWD) [24] that primarily encompassed MAC layer, mobility, and time-synchronization across the OSI layers (say, cross layer). Although this approach was primarily designed to achieve energy-efficiency, the author [24] recommended using a joint routing-MAC concept to achieve better performance in “pseudo-mobility” conditions. However, they confined their suitability to slow movement, especially crafted towards healthcare sector. In contrast, in our work we intended to design a robust routing protocol suitable for major IoT/M2M and their associated WSN based communication purposes. Structurally, EEAWD encompassed PHY and MAC layers with topology constraints. To achieve energy-efficiency, authors focused on minimizing relay nodes or forwarding nodes. EEAWD [24] recommended traffic management with TDMA resource access control, which can be considered as near Cog-MAC or JCMAC. EEAWD recommended syn-

Table 3: *Qualitative assessment.*

Protocol	Energy	PDR	Link	Velocity	Congestion	Delay	Residual Time	Buffer
[10]	-	Yes	-	-	-	Yes	-	-
[11][12]	-	-	-	-	Yes	-	-	-
[14]	Yes	-	-	-	-	Yes	-	-
[15]	-	Yes	-	-	-	-	-	-
[16][27][29]	Yes	-	-	-	-	-	-	-
[17]	Yes	-	-	-	Yes	-	-	-
[20]	-	-	-	-	-	-	-	Yes
[24]	Yes	-	-	-	Yes	-	-	Yes
[31]	-	-	Yes	-	Yes	Yes	-	-
[33]	Yes	-	-	-	-	Yes	-	-
[35]	-	-	-	-	-	-	Yes	-
[37]	-	-	Yes	-	Yes	-	-	-
[38]	-	-	-	-	-	-	-	Yes
[41]	Yes	Yes	Yes	-	-	-	-	-
[43]	-	Yes	-	-	Yes	-	-	Yes
[45]	-	-	Yes	-	Yes	-	-	Yes
JSMCRP	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes

chronization across connecting sensor nodes. PNMK enables our solution to meet mobility-support demands. Additionally, the EEAWD model does not consider any traffic classification or service differentiation provision. Our proposed model incorporates a highly robust data-type and deadline sensitive prioritization and resource scheduling model which makes it more robust for real-time WSN communication demands. Noticeably, in [24], authors could merely hypothesize about their concept. We developed the same approach to assess the relative efficiency of the proposed JSMCRP protocol. The relative performance assessment was done in terms of packet delivery rate (i.e., throughput), packet loss rate, delay, etc. We examined the efficiency of the proposed routing protocol by varying node-density as well as payload conditions, which is common in contemporary WSN application environments. This assessment has been done to verify JSMCRP can cope with the IoT demands.

4.2.1 Performance Assessment with Varying Node Density

With an increase in node density, the congestion probability as well as resource access or allied demand increases. In such cases, ensuring optimal routing and MAC model becomes necessary. Realizing this fact, we examined our proposed routing protocol by varying node density (10, 20, 30, 40, 50, and 60 nodes distributed across 100×100 network region). Thus, varying the node density parameter, the PDR was obtained using Eq. (13) and plotted (Fig. 2). We simulated the existing model (though, this model was developed on our own, as per [24]) to assess performance by both the EEAWD and JSMCRP protocols. The proposed JSMCRP protocol achieves a higher PDR (maximum 99.01 %), which is almost 16 % more than the EEAWD MAC model. JSMCRP exhibits more robustness than the existing approach. Similarly, Packet Loss Ratio (PLR), which was obtained as the difference of hundred minus PDR (Eq. (23)), was obtained and plotted (Fig. 3).

$$\mathrm{PLR}_{ij} = 100 - \mathrm{PDR}_{ij} \tag{23}$$

As depicted in Fig. 3, the JSMCRP routing protocol exhibits a lower PLR (almost 1 %) compared to the EEAWD protocol. The key reason behind such robustness is the provision of distinct buffers, multiple parameter based adaptive routing decisions, and advanced MAC control or JCMAC. Our proposed JSMCRP protocol applies multiple decisive (dynamic) factors to perform routing decisions. These factors include link quality, packet injection rate, and congestion probability. These are used to identify a relay, or the best forwarding node, with most suitable features when transmission or forwarding occurs. This mechanism ensures reliable and QoS centric transmission (Figs. 2–4).

The majority of the existing MAC models or routing approaches, where classical sleep-awake scheduling is applied, suffer from delay. This problem can be even more severe in case of a contemporary mobile IoT ecosystem or during M2M communication where there can be non-linear random communication demands. In such cases, ensuring delay-resilient transmission is a must. Considering this goal, we examined delay performance in our proposed routing protocol by varying node density. Increasing node density can provide multiple neighbouring nodes to make relaying decisions. However, exploring their respective node tables and identifying a single forwarding node from a set of multiple nodes (causing large search space) can be time consuming.

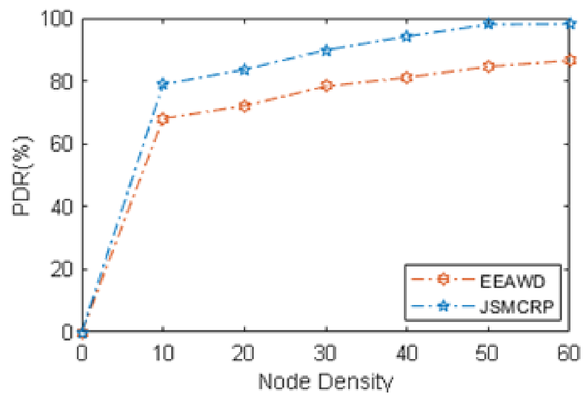

Fig.2: *PDR performance vs node density.*

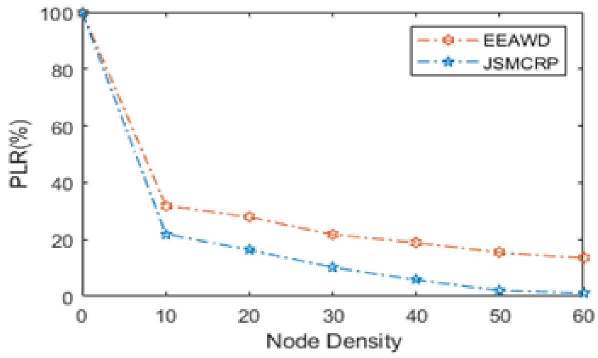

Fig.3: *PLR performance vs node density.*

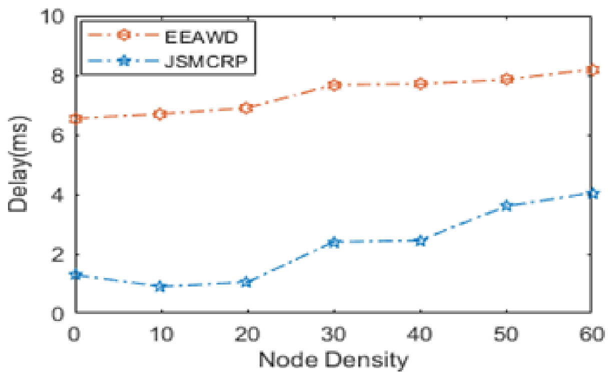

Fig.4: *End-to-end delay performance vs node density.*

Even applying multiple network/node parameters to identify a single BFN can be complex and time consuming. In such cases, maintaining low latency or delay is a must. With this goal, we examined delay performance of our JSMCRP protocol using Eq. (23) and found it to be more time efficient due to its PNMK together with its dynamic parameter update ability. Once obtaining the BFN node, the source and destination pair is obtained, between which the delay is estimated.

$$\begin{aligned}\text{Link}_{\text{Delay}_i,n} &= \frac{\text{ARTT}_n}{2} \\ &= \left(\text{Delay}_{\text{MAC}}+\text{Delay}_{\text{Queue}}+\text{Delay}_{Tx}\right)\times C_i^j\end{aligned} \tag{24}$$

In Eq. (24), $\text{Delay}_{\text{MAC}}$ signifies the channel access delay, $\text{Delay}_{\text{Queue}}$ presents the queuing delay, and the transmission delay is given by Delay_{Tx}. The parameter C_i^j presents the total number of packets transmitted.

Fig. 4 shows that our JSMCRP protocol outperforms existing EEAWD routing and/or MAC models. Interestingly, our proposed JSMCRP routing protocol exhibits better performance with higher node density. Such robustness can be attributed to increased neighbour nodes having pre-assigned buffers and adaptive MAC scheduling, which assigns resources as per priority and network demands. It affirms the suitability of JSMCRP for networks with high node density, such as IoT systems or different M2M communications.

4.2.2 Performance Assessment with Varying Payload

Similar to the varying node condition assessment, we examined performance by varying payload. The presence of sufficient neighbouring nodes provides sufficient search space to perform routing decisions. However, increased payload might cause a situation where a node might find itself in a resource constrained condition. In other words, an increased payload condition for both RPT as well as NR2D might force JSMCRP to reach a complex situation impacting performance. In such approaches, even MAC is required to be sufficient enough to provide dynamic or adaptive resource access to ensure higher performance (PDR, PLR) while ensuring delay-resilient transmission. Considering this fact, we assessed the performance of our proposed JSMCRP routing protocol by varying payload conditions. Figs. 5–7 present PDR, PLR, and delay performance of our proposed adaptive MAC assisted dynamic (adaptive) WSN routing protocol. As depicted in Fig. 5, the PDR performance by our proposed JSMCRP routing protocol is higher than the EEAWD routing or MAC models. Our proposed JSMCRP routing protocol exhibits a maximum PDR of 98.2 %, which is almost 18 % higher than the EEAWD protocol (82.01 %). Similarly, PLR performance (Fig. 6) also affirms the robustness of our proposed model, where JSMCRP exhibits a minimum PLR of 1.8 %, while EEAWD exhibits almost 18 % PLR. These results display the robustness of our proposed joint-synchronous MAC-routing approach. The use of enhanced adaptive and cognitive MAC features enables our JSMCRP protocol to maintain better resource allocation. At the same time, the multiple network/node parameter

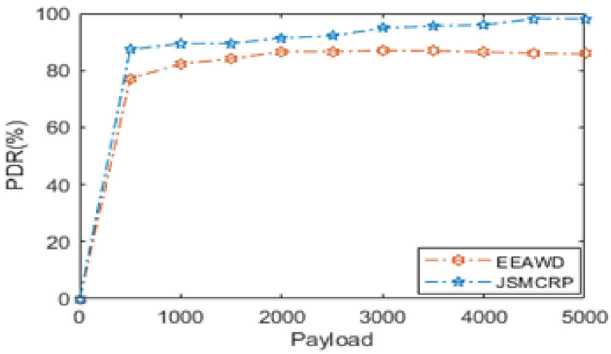

Fig. 5: *PDR performance vs payload (packets).*

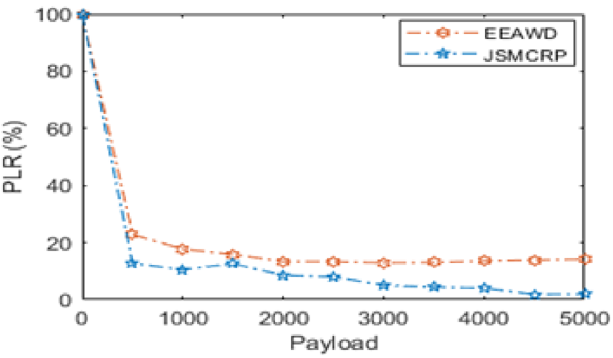

Fig. 6: *PLR performance vs payload (packets).*

based routing or relaying model strengthens JSMCRP to achieve higher performance.

Similar to Fig. 4, JSMCRP ensures maintaining low end-to-end delay compared to the existing method. JSMCRP applies a deadline sensitive routing concept where it assesses each node for its transmission rate ability or packet injection capacity. This approach strengthenes JSMCRP to ensure timely data delivery without violating deadline time. Results (Figs. 4 and 7) confirm the time-efficient communication or transmission ability of JSMCRP. Since in this work the predominant emphasis was made on ensuring QoS centric communication (by maintaining reliable data transmission, low redundancy, low latency, low packet loss, and hence low retransmission ability), we assessed it in terms of PDR, PLR, and delay.

Since the JSMCRP protocol delivers up to 98 % of data successfully, it imposes little or no retransmission. It helps maintain low energy consumption. As cumulative solution, the JSMCRP protocol is a robust and efficient QoS centric adaptive (cognitive) MAC-enabled routing approach which yields optimal performance for WSN based IoT and/or M2M communication. In our proposed JSMCRP model, the majority of time consumption takes place during BFN or BFP selection, which is then followed by resource allocation using the DTAPS model. This ensures that the data or payload is provided fair resources

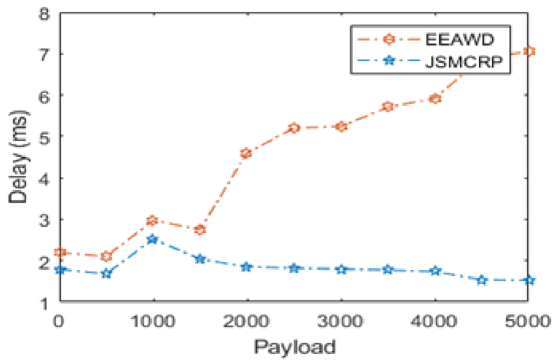

Fig. 7: *End-to-end delay performance vs payload (packets).*

either from the RTD buffer or the NRT buffer. This mechanism avoids retransmission or wait periods. In other words, the major delay occurs only during BFN or BFP selection, which is the initial phase of routing. Once the routing is established, our proposed DTAPS model achieves optimal performance while ensuring optimal resource allocation to all data traffic. This is the reason the proposed model takes a bit more time in the initial phase, while in the later periods, even with increase in payload, it maintains lower delay (Fig. 7). The major delay takes place at the inception of route formation, mainly due to BFN selection and BFP formation. On the other hand, the existing EEAWD protocol does not have any dedicated provision for traffic sensitive resource allocation (especially for real-time as well as non-real time traffic together) and therefore it can undergo data drops, causing retransmission that as a result could impose higher delay (Fig. 7).

5. CONCLUSION

This work mainly intended to exploit cross-layer information from the IEEE 802.15.4 protocol stack, which is the native OSI structure for WSN to perform "Network Adaptive Routing Decisions" and "Adaptive MAC Scheduling". Unlike major existing cross-layer approaches where merely network or MAC layers are considered for routing decisions, this work exploited the application, network, MAC, and PHY layers to enable a robust "Cross-layer architecture based Joint-Synchronous MAC and Routing Protocol for WSN communication (JSMCRP)". Functionally, JSMCRP embodies key features such as Data Traffic Assessment, Prioritization and Scheduling (DTAPS) at application layer, Proactive Network Monitoring and Knowledge function (PNMK), Dynamic Congestion Index Estimation (DCIE), and Cumulative Rank Sensitive Routing Decision (CRSRD) at the network layer. It uses Adaptive Link Quality, Packet Injection Rate, and JSMCRP Cognitive MAC (JCMAC) as the IEEE 802.15.4 MAC. Our proposed JSMCRP protocol has multiple contributions and novelties such as DTAPS assisted traffic classification, buffer allocation, prioritization and fair resource scheduling, deadline sensitive relaying decisions, a multiple node parameters based relaying concept, and adaptive MAC scheduling. Such robustness enables the JSMCRP protocol to exhibit time-efficient and reliable data transmission over WSNs. Being a cross-layered structure, it incorporated synchronized decision making or computation between the different layers, which enabled it to be time-efficient as well as adaptive. On the other hand, the MAC model was applied as an adaptive scheduler which exploits node and/or network information dynamically to perform resource access and control. The functional approach means JSMCRP should be referred to as Adaptive (Cognitive) MAC (JCMAC) based Dynamic Routing Model to meet QoS demands. Simulation results confirmed that the proposed JSMCRP protocol exhibits higher PDR (almost 99 %), lower PLR (approximately 1 %), and significantly low delay (approximately 1–2 ms) even under varying payload and (network) density conditions, in comparison to the state-of-art Energy-Aware Topology Design for Wireless Body Area Networks (EEAWD) protocol, which also exploits a MAC-aware, joint routing concept for wireless communication. Although the proposed protocol achieves satisfactory performance, it could not address traffic adaptive multi-rate PHY switching, which could yield more energy-efficient and resource efficient routing over constrained WSNs. It can be considered as an area to explore for further enhancement of our JMSCRP protocol.

References

[1] S. Ehsan and B. Hamdaoui, "A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 2, pp. 265–278, Second Quarter 2012.

[2] P. Spachos, D. Toumpakaris, and D. Hatzinakos, "QoS and energy-aware dynamic routing in Wireless Multimedia Sensor Networks," in *2015 IEEE International Conference Communications (ICC)*, 8–12 June 2015, pp. 6935–6940.

[3] J. Sen and A. Ukil, "An adaptable and QoS-aware routing protocol for Wireless Sensor Networks," in *2009 1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronics Systems Technology*, 17–20 May 2009, pp. 767–771.

[4] K. Khanke and M. Sarde, "An Energy Efficient and QoS Aware Routing Protocol for Wireless Sensor Network," *International Journal of Advanced Research in Computer and Communication Engineering*, vol. 4, no. 7, pp. 355–358, July 2015.

[5] L. Lombardo, S. Corbellini, M. Parvis, A. Elsayed, E. Angelini, and S. Grassini, "Wireless Sensor Network for Distributed Environmental Monitoring," *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 5, pp. 1214–1222, May 2018.

[6] A. Boukerche and R. W. Nelem Pazzi, "Lightweight mobile data gathering strategy for wireless sensor networks," in *2007 9th IFIP International Conference on Mobile Wireless Communications Networks*, 2007, pp. 151–155.

[7] G. M. de Araújo and L. B. Becker, "A Network Conditions Aware Geographical Forwarding Protocol for Real-Time Applications in Mobile Wireless Sensor Networks," in *2011 IEEE International Conference on Advanced Information Networking and Applications*, 2011, pp. 38–45.

[8] N. Mansoor, A. K. M. M. Islam, M. Zareei, and C. Vargas-Rosales, "RARE: A Spectrum Aware Cross-Layer MAC Protocol for Cognitive Radio Ad-Hoc Networks," *IEEE Access*, vol. 6, pp. 22210–22227, 2018.

[9] A. Katiyar, J. Kumar, and P. M. Khilar, "Adaptive MAC Protocol in Wireless Sensor Networks for Disaster Detection," in *Progress in Computing, Analytics and Networking* (Advances in Intelligent Systems and Computing 710), P. Pattnaik, S. Rautaray, H. Das, and J. Nayak, Eds. Singapore: Springer, 2018.

[10] R. Singh, B. K. Rai, and S. K. Bose, "A Novel Framework to Enhance the Performance of Contention-Based Synchronous MAC Protocols," *IEEE Sensors Journal*, vol. 16, no. 16, pp. 6447–6457, Aug. 2016.

[11] R. Singh, B. K. Rai, and S. K. Bose, "A contention-based routing enhanced MAC protocol for transmission delay reduction in a multi-hop WSN," in *2017 IEEE Region 10 Conference (TENCON 2017)*, Penang, Malaysia, 2017, pp. 398–402.

[12] R. Singh, B. K. Rai, and S. K. Bose, "A Joint Routing and MAC Protocol for Transmission Delay Reduction in Many-to-One Communication Paradigm for Wireless Sensor Networks," *IEEE Internet of Things Journal*, vol. 4, no. 4, pp. 1031–1045, Aug. 2017.

[13] A. Mendez Perez, M. Panduro Mendoza, J. Huerta Mendoza and A. Reyna Maldonado, "Performance Evaluation of MAC Protocol and Routing in Multi-Rate Wireless Ad-Hoc Networks," *IEEE Latin America Transactions*, vol. 13, no. 1, pp. 84–89, Jan. 2015.

[14] M. Arifuzzaman, O. A. Dobre, M. H. Ahmed, and T. M. N. Ngatched, "Joint Routing and MAC Layer QoS-Aware Protocol for Wireless Sensor Networks," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Wash-

ington, DC, USA, 2016, pp. 1–6.

[15] M. Sefuba and T. Walingo, "Energy-efficient medium access control and routing protocol for multihop wireless sensor networks," *IET Wireless Sensor Systems*, vol. 8, no. 3, pp. 99–108, 2018.

[16] S. Chen, Z. Yuan, and G. M. Muntean, "Balancing Energy and Quality Awareness: A MAC-Layer Duty Cycle Management Solution for Multimedia Delivery Over Wireless Mesh Networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 2, pp. 1547–1560, Feb. 2017.

[17] J. A. Haqbeen, T. Ito, M. Arifuzzaman, and T. Otsuka, "Joint routing, MAC and physical layer protocol for wireless sensor networks," in *2017 IEEE Region 10 Conference (TENCON 2017)*, Penang, Malaysia, 2017, pp. 935–940.

[18] Y. Liu, Q. Chen, H. Liu, C. Hu, and Q. Yang, "A Non Destructive Interference based receiver-initiated MAC protocol for wireless sensor networks," in *2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, Las Vegas, NV, USA, 2016, pp. 1030–1035.

[19] D. T. C. Wong, Q. Chen, X. Peng, and F. Chin, "Performance analysis of multi-channel pure collective Aloha MAC protocol for satellite uplink access," in *2017 IEEE Region 10 Conference (TENCON 2017)*, Penang, Malaysia, 2017, pp. 164–169.

[20] Y. Liu, H. Liu, Q. Yang, and S. Wu, "RM-MAC: A routing-enhanced multi-channel MAC protocol in duty-cycle sensor networks," in *2015 IEEE International Conference on Communications (ICC)*, London, UK, 2015, pp. 3534–3539.

[21] S. Mohapatra and R. K. Mohapatra, "Comparative analysis of energy efficient MAC protocol in heterogeneous sensor network under dynamic scenario," in *2017 2nd International Conference on Man and Machine Interfacing (MAMI)*, Bhubaneswar, India, 2017, pp. 1–5.

[22] M. I. Khalil, M. A. Hossain, M. J. Haque, and M. N. Hasan, "EERC-MAC: Energy efficient Receiver Centric MAC protocol for Wireless Sensor network," in *2017 IEEE International Conference on Imaging, Vision & Pattern Recognition (icIVPR)*, Dhaka, Bangladesh, 2017, pp. 1–5.

[23] T. Senthil and Y. B. Samuel, "Energy efficient hop extended MAC protocol for wireless sensor networks," in *2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies*, Ramanathapuram, India, 2014, pp. 901–907.

[24] L. Lahlou, A. Meharouech, J. Elias, and A. Mahout, "MAC-network cross-layer energy optimization model for Wireless Body Area Networks," in *2015 International Conference on Protocol Engineering (ICPE) and International Conference on New Technologies of Distributed Systems (NTDS)*, Paris, France, 2015, pp. 1–5.

[25] P. T. Kalaivaani and A. Rajeswari, "An analysis of H-MAC, HSMAC and H-MAC based AOMDV for wireless sensor networks to achieve energy efficiency using spatial correlation concept," in *2015 2nd International Conference on Electronics and Communication Systems (ICECS)*, Coimbatore, India, 2015, pp. 796–801.

[26] Y. Peng, Z. Li, W. Zhang, and D. Qiao, "A lifetime-balancing MAC protocol under the end-to-end delay requirement," *Journal of Communications and Networks*, vol. 19, no. 1, pp. 51–64, Feb. 2017.

[27] O. Bouachir, A. Ben Mnaouer, F. Touati, and D. Crescini, "EAMP-AIDC - energy-aware mac protocol with adaptive individual duty cycle for EH-WSN," in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, Valencia, Spain, 2017, pp. 2021–2028.

[28] M. Thenmozhi and S. Sivakumari, "Adaptive energy efficient and rate adaptation based medium access control routing protocol (AEERA — MACRP) for fully connected wireless ad hoc networks," in *2017 8th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Delhi, india, 2017, pp. 1–7.

[29] C. Venkataramanan and S. M. Girirajkumar, "EARMP: A unified application specific MAC protocol for wireless sensor networks," in *International Conference on Information Communication and Embedded Systems (ICICES2014)*, Chennai, india, 2014, pp. 1–5.

[30] B. Cheng, L. Ci, C. Tian, X. Li, and M. Yang, "Contention Window-Based MAC Protocol for Wireless Sensor Networks," in *2014 IEEE 12th International Conference on Dependable, Autonomic and Secure Computing*, Dalian, China, 2014, pp. 479–484.

[31] S. Kurumbanshi and S. V. Rathkanthiwar, "MAC time & delay analysis of exponentially distributed nodes in adhoc network," in *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*, Paralakhemundi, india, 2016, pp. 1429–1434.

[32] S. Zhuo, Z. Wang, Y. Q. Song, Z. Wang, and L. Almeida, "A Traffic Adaptive Multi-Channel MAC Protocol with Dynamic Slot Allocation for WSNs," *IEEE Transactions on Mobile Computing*, vol. 15, no. 7, pp. 1600–1613, July 2016.

[33] S. Rachamalla and A. S. Kancharla, "Power-Control Delay-aware routing and MAC protocol for Wireless Sensor Networks," in *2015 IEEE 12th International Conference on Networking, Sensing and Control*, Taipei, Taiwan, 2015,

pp. 527–532.

[34] S. Khaliq and S. Henna, "HE-PRMAC: Hop extended pipelined routing enhanced MAC protocol for wireless sensor networks," in *2016 Sixth International Conference on Innovative Computing Technology (INTECH)*, Dublin, Ireland, 2016, pp. 392–397.

[35] Ananda Babu J, Siddaraju, and Guru R, "An energy efficient routing protocol using RD-MAC in WSNs," in *2016 2nd International Conference on Applied and Theoretical Computing and Communication Technology (iCATccT)*, Bangalore, India, 2016, pp. 799–803.

[36] C. Li, Y. Xu, B. Diao, Q. Wang, and Z. An, "DBR-MAC: A Depth-Based Routing Aware MAC Protocol for Data Collection in Underwater Acoustic Sensor Networks," *IEEE Sensors Journal*, vol. 16, no. 10, pp. 3904–3913, May 2016.

[37] A. Wahid, I. Ullah, O. A. Khan, A. W. Ahmed, and M. A. Shah, "A new cross layer MAC protocol for data forwarding in underwater acoustic sensor networks," in *2017 23rd International Conference on Automation and Computing (ICAC)*, Huddersfield, UK, 2017, pp. 1–5.

[38] L. Leao, V. Felea, and H. Guyennet, "MAC-Aware Routing in Multi-Sink WSN with Dynamic Back-Off Time and Buffer Constraint," in *2016 8th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, Larnaca, Cyprus, 2016, pp. 1–5.

[39] J. Seddar, H. Khalifé, W. Al Safwi, and V. Conan, "A full duplex MAC protocol for wireless networks," in *2015 International Wireless Communications and Mobile Computing Conference (IWCMC)*, Dubrovnik, Croatia, 2015, pp. 244–249.

[40] T. Heimfarth, J. C. Giacomin and J. P. d. Araujo, "AGA-MAC: Adaptive Geographic Anycast MAC Protocol for Wireless Sensor Networks," in *2015 IEEE 29th International Conference on Advanced Information Networking and Applications*, Gwangiu, China, 2015, pp. 373–381.

[41] A. M. Akhtar, A. Behnad, and X. Wang, "Cooperative ARQ-Based Energy-Efficient Routing in Multihop Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 11, pp. 5187–5197, Nov. 2015.

[42] P. C. Reddy and N. V. S. N. Sarma, "An energy efficient routing and MAC protocol for Bridge Monitoring," in *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, Chennai, China, 2016, pp. 312–315.

[43] T. Tsuboi, T. Ito, C. Hitsu, and H. Ueda, "Proposed multi-channel Ad-hoc network with cross-layer design of MAC and routing protocols," in *2015 10th Asia-Pacific Symposium on Information and Telecommunication Technologies (APSITT)*, Colombo, Sri Lanka, 2015, pp. 1–3.

[44] T. H. Hsieh, K. Y. Lin, and P. C. Wang, "A hybrid MAC protocol for wireless sensor networks," in *2015 IEEE 12th International Conference on Networking, Sensing and Control*, Taipei, Taiwan, 2015, pp. 93–98.

[45] L. Louail, V. Felea, J. Bernard, and H. Guyennet, "MAC-aware routing in wireless sensor networks," in *2015 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, Constanta, Romania, 2015, pp. 225–229.

[46] P. Gonizzi, P. Medagliani, G. Ferrari, and J. Leguay, "RAWMAC: A routing aware wave-based MAC protocol for WSNs," in *2014 IEEE 10th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Larnaca, Cyprus, 2014, pp. 205–212.

[47] A. Koubaa, M. Alves, E. Tovar, "Time Sensitive IEEE 802.15.4 Protocol," in *Sensor Networks and Configuration: Fundamentals, Techniques, Platforms, and Experiments*, N. P. Mahalik, Ed. Berlin, Germany: Springer-Verlag, 2007, pp. 19–49.

[48] W. Du, D. Navarro, and F. Mieyeville, "Performance evaluation of IEEE 802.15. 4 sensor networks in industrial applications," *International Journal of Communication Systems*, vol. 28, no. 10, pp. 1657–1674, 2015.

[49] A. Woo and D. Culler, "Evaluation of efficient link reliability estimators for low-power wireless networks," EECS Department, University of California, Berkeley, USA, Technical Report UCB/CSD-03-1270, 2003.

Shruti Birur Viswanath received her B.E. in Computer Science and Engineering from Malnad College of Engineering, Hassan, Visveswaraya Technology University, India, in 2005. She received her M.Tech. in Computer Science and Engineering from Siddaganga Institute of Technology, Tumkur, Visveswaraya Technology University, India, in 2009. She is currently pursuing a Ph.D. at Nitte Meenakshi Institute of Technology (NMIT). She is an Assistant Professor at Department of Computer Science and Engineering (CSE), Nitte Meenakshi Institute of Technology, Bengaluru, India.

Her research interests include the fields of wireless sensor networks and ad-hoc networks.

Thippeswamy M. Nagendrappa received his B.E. (CSE) from JNNCE, Shimoga, Kuvempu University, India. He has a M.Tech. (CSE) Degree from MSRIT, VTU, Bengaluru, India. He completed his Doctorate Degree from Howard College Campus, the University of KwaZulu-Natal, Durban, South Africa. He is a Professor and the Head of the Department of Computer Science and Engineering (CSE), Nitte Meenakshi Institute of Technology, Bengaluru, India.

Prof. Thippeswamy is a hard-working creative professional and senior academician with 20+ years of experience and 5+ years of research experience. He has worked in well-known colleges in Karnataka state and at African universities. He has applied for 8 patents, co-authored books and book chapters, and published 17 journal papers and 42 conference papers. He is a recipient of the UKZN doctoral fund to design an energy-efficient MAC protocol for WSN from the University of KwaZulu-Natal, Durban, South Africa. He has received a research grant of 15,000 ZAR (Grant in Rands) for developing data gathering algorithms for WSNs. He has completed 8 research projects sponsored by various agencies of the Government of India and the Government of Karnataka and for private software companies. His interest areas are in the areas of IoT, big data analytics, and wireless sensor networks.

Krishna Rao Venkatesh received his B.E. Electronics from Bangalore University, India, in 1973, M.Tech. from Indian Institute of Science, Bangalore, India, in 1975. He also has a M.Comp. Science from Concordia University, Canada. He completed his Ph.D in Computer Science from Concordia University, Canada. He is a Professor at NITTE Meenakshi Institute of Technology. He has vast experience in industry and Academia. His areas of interest is distributed systems.