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ORIGINAL RESEARCH

A joint hybrid corona based opportunistic routing design with quasi mobile sink for IoT based wireless sensor network

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Abstract
The resource constrained wireless sensor embedded devices are deployed in the edge of the Internet of Things (IoT) system for smart monitoring and control of large scale Wireless Sensor Network (WSN) applications. A joint hybrid corona based Opportunistic Routing (OR) with path-constrained Quasi-Mobile Sink (QMS) is designed to address the challenges for (i) providing long term sustainable operation and scalability of WSN (ii) also counteract the hot-spot problem near the sink. This hybrid routing design adopted opportunistic mode of forwarding as it's first and last resort to increase transmission reliability, despite the time varying lossy radio links. The eligible relay-set based on the corona level it resides with respect to sink, collaborates for packet forwarding in a fully distributed online manner during the opportunistic mode. The priority order of relay(s) are determined on the fly based on multi-metrics fuzzy decision logic for timer based coordination and adopts a cross layered differentiated back off strategy for distributed priority based contention. The routing design switches to unicast mode of forwarding via the most trusted relay(s) for subsequent transmissions to increase the energy efficiency under stable link conditions. Simulation results shows that hybrid OR design achieves high end to end packet delivery ratio and minimizes the average energy consumed per node in comparison with existing routing protocol designs. The joint routing design with QMS is found to scale well and prevents the unbalanced energy consumption by minimizing the maximum energy dissipation and normalized energy consumption per packet compared to the Static Sink (SS) and Uncontrolled Mobility Model based Sink (UMM-S).

Keywords Routing · Sink · Opportunistic · Corona · Low power · Fuzzy logic · Lossy links · WSN · IoT

1 Introduction

Evolution of Wireless multi-hop networks has branched its wings into several sub domains as shown in Fig. 1 such as Ad hoc networks, Wireless Mesh networks (WMN), Vehicular Ad hoc Network (VANET), Device to Device (D2D) 5G communication etc.

WSN and it's allied Low power Lossy Networks (LLN) in this IoT era has been catering numerous smart applications (Mainetti et al. 2011) and plays a significant role for automation of monitoring and control applications as part of Industry 4.0 (Koutsiamanis et al. 2020). WSN is one of the key drivers for the realization of IoT applications. The need for long term, sustainable operation via energy efficient protocol design arises as these smart sensing wireless devices are battery operated. These tiny embedded wireless nodes are required to operate with limited power and are built with low cost hardware constrained in bandwidth. The advancement of hardware systems for IoT is also an active research domain of large scale WSN (Amirinasab et al. 2020). Sensor nodes cannot be easily replenished due to remote deployment for certain applications (Yue and He 2018) with reduced human intervention. The issue of scalability arises for applications which demand larger coverage area and may involve several hundreds to thousands of low power wireless devices to be deployed.

The packets generated by the sensor nodes need to be transmitted wirelessly to the sink for data collection in a direct single-hop or routed via intermediate nodes in a multi-hop manner. IEEE 802.15.4 compliant low power, short ranged radios are typically used in many IoT applications. The radio links exhibits temporal variations and are asymmetric in nature (Cerpa et al. 2005). Several environment

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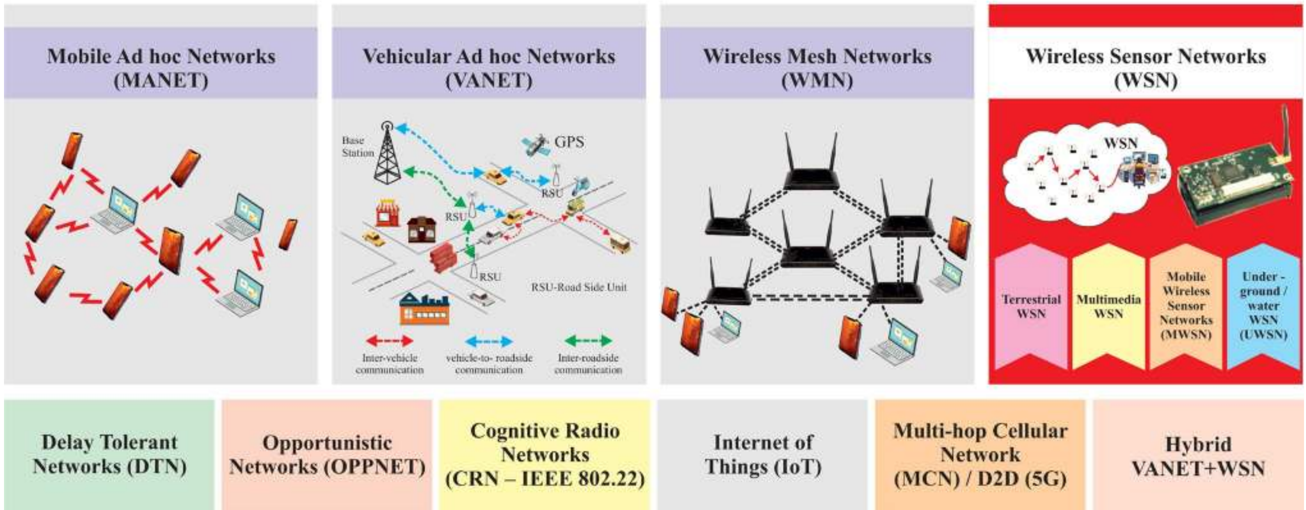

Fig. 1 Sub-domains of Wireless Multi-hop network

factors due to weather conditions, presence of obstacles, interim connectivity issues due to movement of objects, multi-path fading, interference induced from neighboring wireless technologies or concurrent transmissions results in high variances in radio links and thus incurs higher Packet Error Rate (PER) in such lossy wireless networks. Hence, a cross layered algorithmic design is necessary by integrating the routing and Medium Access Control (MAC) layers in order to achieve reliability, energy efficiency and scalability despite unreliable wireless medium. Due to the erroneous nature of the radio links, the next hop node chosen a priori in traditional routing schemes might fail to successfully receive the packet and possibly incur additional retransmissions. The OR approach shifts the paradigm by avoiding pre-selection of relay candidate before data transmission and instead rely on the fly, distributed online forwarding decision after data transmission. The challenges involved in the existing design of OR are constant overhearing and periodic beaconing by constrained sensor nodes, that needs to be addressed for energy efficient operation in IoT based WSN (Rosario et al. 2014).

The traffic pattern in WSN is typically many to one converge-cast pattern. The sink node acts as the edge gateway to the external network interface and cloud infrastructure of the end to end IoT system. The sink has no constraints in power supply and acts as the destination for traffic generated by several sensor nodes. This poses challenge such as hot-spot or funneling effect in the sink's neighbourhood (Gu et al. 2015). The sensor nodes in the hot spot region may need to relay heavy traffic for all the other nodes that are away from the sink, causing rapid battery depletion and network partition in the worst case.The hot-spot problem needs to be jointly addressed via sink mobility irrespective of the strength of routing design. The objective is to develop a scalable routing protocol design and balance the load and energy consumption in the error-prone IoT based WSN.

The significant contributions proposed in this work are as follows.

1. An **OP**portunistic, **S**calable, **E**nergy efficient **R**outing (OPSER) design is proposed to operate in hybrid mode. The opportunistic mode of data forwarding will be the first and last resort for achieving high end to end data delivery and energy efficiency. The unicast mode of forwarding will be used for successive transmissions to the trusted relay nodes that was chosen dynamically in opportunistic mode till transmissions are successful without link-level error.
2. A fully distributed, on the fly, online forwarding decision by the eligible relay set is proposed using a priority-based timer coordination mechanism. A fuzzy based decision logic is adopted by the relay set to determine its priority order and the dynamic holding time before contending for the channel with differentiated back-off exponent assignment in IEEE 802.15.4 MAC.
3. The cross layered metrics for high priority candidacy using fuzzy decision logic includes the Link Quality Indicator (LQI), Trust degree of the relay candidate, corona level and residual energy beyond the minimum threshold.
4. Instead of multiple-mobile sinks, a joint design with Quasi-Mobile single Sink (QMS) is proposed as a solution to combat the hot-spot problem.
5. A corona driven interest propagation by the QMS to balance the topological query updates and an alternative to the traditional Global Positioning System (GPS) driven/ location estimation routing schemes is implemented.

Section 2 focus on the related work, Sect. 3 elaborates the proposed design. Section 4 presents the mathematical analysis. Section 5 presents the simulation results and performance evaluation.

2 Related work

Khan et al. (2014) presents a comprehensive survey of data gathering mechanism via sink mobility schemes such as Fixed Path, Controlled and Random Mobility. It has been proven that mobilizing the sink is better than keeping it static to achieve energy savings (Luo and Hubaux 2010; Singh and Kumar 2020) and combat the hot spot problem near the sink. The controlled mobility scheme involves guiding or controlling the movement of sink based on the objective function or observable events or parameter of interest in the deployed network. The controlled mobility schemes incur heavy communication cost overhead to gather global topology related information updates to move towards that area of interest. The random mobility scheme i.e., Uncontrollable Mobility Model (UMM) (Gu et al. 2015) causes unexpected changes in topology and introduce excessive protocol overhead for maintenance of routes. The issues such as location update of the sink and mobility aware routing of data packets becomes a challenge. The fixed path mobility scheme impose a path constrained programmed fixed movement pattern of the sink and is not influenced by the network behavior at run time. This type of scheme can potentially balance the topological updates and suppress the protocol overhead imposed by the sink mobility pattern. The necessity for joint routing with fixed path constrained sink mobility is the focus of this research work. Hot spot problem near the sink was tackled either via sensor node deployment strategies (Rahman et al. 2016) or to increase the quantity of nodes in the sink's neighborhood (Rivas et al. 2006) or to use multiple mobile sinks (Xie et al. 2014; Koosheshi and Ebadi 2019) to collect data in direct single hop or few hops. Ma et al. (2020) deploys the drone that acts as data sink to gather data from sensor nodes and employs flooding based concurrent transmission communication paradigm instead of routing. The trade-off has been the cost and latency involved to optimize the energy consumption in the network.

Several dynamic routing designs for WSN over lossy radio links as proposed over the past years that primarily falls in the proactive, reactive, hybrid, geographical, clustering, real-time or opportunistic routing categories. Geographic routing adopts a distributed hop by hop routing approach and operates in a localized manner. These are scalable solutions as they avoid gathering the global topology or overhead due to table exchanges as compared to proactive or reactive designs. IETF pointed out the detrimental consequences of integrating GPS onto low power constrained nodes (Tripathi et al. 2014). Ahmed (2015) highlights the pros and cons of geographical based and corona aware routing mechanism in WSN. Beacon based OR such as Biswas and Morris (2005), Kim and Ravindran (2009), Luo et al. (2014), Wu et al. (2018), Fradj et al. (2019) increases the signaling overhead and the predefined relay nodes list in the packet header might not reflect the real situation at the moment of the packet transmission. The reasons may be due to fluctuations in signal strength, environmental change impact, malfunction in node, sleep state and nodes mobility. An analysis of few routing designs in each category of routing from the energy efficiency and large-scale suitability point of view is presented in Table 1.

3 Proposed work

3.1 Network model

The large scale WSN is modeled as a dynamic graph G(V,E) where,

- 'V' represents the sensor nodes in the network,
- 'E' represents the radio links between nodes that are within the transmission range (R) of each other in the network,
- w(u,v) is the lossy link weight that depends on the spatial and temporal variations due the channel fluctuations, u,v $\in$ V(G).
- The Corona Interest Propagation (CIP) is initiated by the sink and forms a Destination Oriented Directed Acyclic Graph (DODAG) towards the root node (sink).
- The depth of the sensor node 'u' is determined in-terms of Corona Level (CL) it resides with respect to the root node.
- Each sensor node 'u' has a battery with initial available energy (E_I).
- The radio transceiver is configured to operate at a fixed transmit power level (P_t).
- The destination of many to one converge-cast traffic from several sources is the sink i.e QMS.
- The QMS acts as the gateway to upload the data gathered in the cloud infrastructure.
- The data packets generated by the source node may need to hop several CLs via the intermediate Relay Nodes (RN_i) where i $\in$ N (Number of sensor nodes in the network) to reach the QMS.

Figure 2 displays the functionalities of the QMS and sensor node(s).

The assumptions of the proposed work are as follows

Table 1 Review of existing routing designs

Routing type	Routing protocol	Key features	Limitations
Real-time routing	RTLD	Forwarder selection based on multiple metrics such as Packet Reception Rate (PRR), Packet Velocity and Residual Energy (Ahmed and Fisal 2008).	Traditional unicast mechanism with MAC level retries in case of link-errors in all these routing designs. Significant control overhead due to route request, replies by eligible forwarders and periodic hello beaconing for neighborhood management in these designs. Location estimation via GPS/ RSSI based mechanism in case of RTLD
Real-time routing	ERTLD	Multiple metrics like RTLD for forwarding node selection with Corona aware flexible tree based routing (Ahmed 2013) .	
Real-time routing	RTPC	Energy efficient forwarder choice using packet velocity as metric to minimize hop count (Xing et al. 2005)	
Reactive routing	AODV	A scalable on-demand reactive routing adopted in Zigbee Mesh Routing	A traditional Unicast mechanism which triggers route maintenance procedures upon link level errors. Broadcast storms for route discovery via route request and unicast route replies
Proactive routing	RPL	DODAG construction towards sink and adopted in 6LoWPAN stack for LLN (Winter et al. 2012)	Periodic Beacon based control traffic schemes increases the protocol overhead and consumes battery and bandwidth
Reactive routing	LOADng	Light weight AODV design to minimize energy consumption in LLN (Clausen et al. 2017)	Not opportunistic design to combat temporal variations in error-prone WSN
OR scheme	EXOR	An 802.11b Test bed implementation to increase throughput in wireless networks via candidate selection, prioritization and timer coordination scheme (Biswas and Morris 2005)	Periodic beacon (hello) based OR schemes increase the overhead and consumes battery, bandwidth in all these designs. The list of selected relay candidates are added in the packet header, that adds to the transmission cost in these designs
OR scheme	POR	A light weight time series prediction method for route determination and couples link quality and location metrics to compute priority of relay candidates (Wu et al. 2018)	
Geographical OR scheme	EEOR	Select and prioritize relay candidates to minimize total energy cost in WSN (Mao et al. 2009)	
Geographical OR scheme	Region Based Collision Avoidance Beaconless Routing	Strategies to avoid duplicate packets in timer based contention mechanism in OR scheme (Lee et al. 2015)	The assumption in these designs is nodes are aware of their locations and sink's location. Energy consumption for location estimation is ignored
Geographical OR scheme	LINGO	A beaconless OR design for mobile multimedia IoT applications uses link quality, distance progress and residual energy for relay candidate selection (Rosario et al. 2014)	

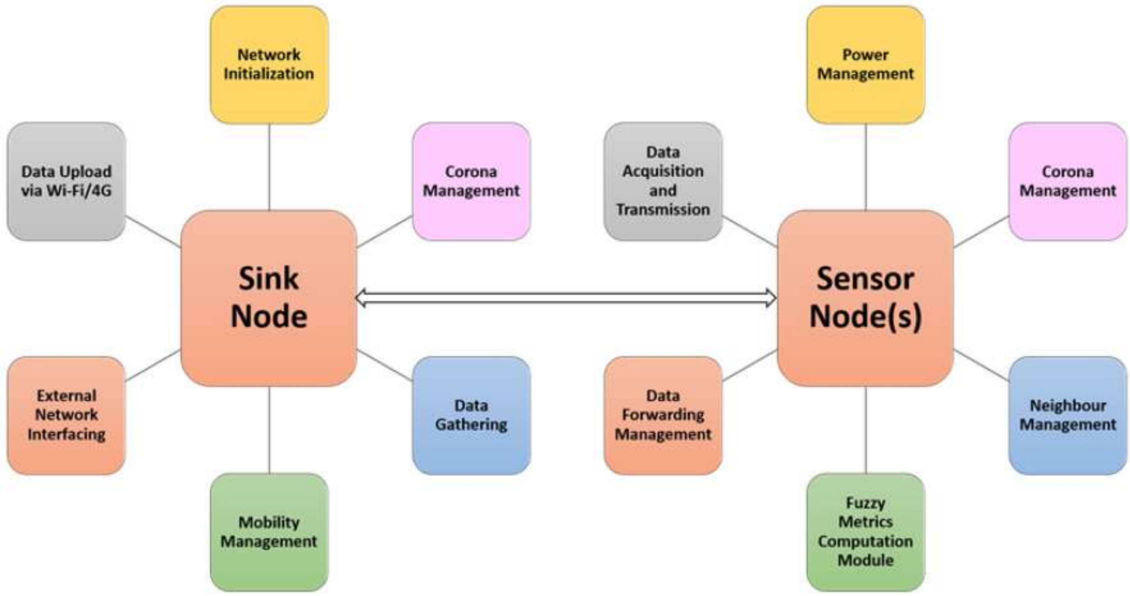

Fig. 2 Sink and sensor node(s) functionalities in WSN

- The deployment area is considered to be two-dimensional grid composed of same cell size.
- Sensor Nodes (SNs) are deployed in a regular grid manner and are stationary.
- The SNs are homogeneous and operate at the same fixed transmission power level chosen based on range test measurements in the environment of interest.
- The QMS can move freely on the grid at unbounded speed and during its sojourn time at the data gathering point, the SNs transmits the sampled data at a constant rate with the QMS.
- Each SN has a limited initial energy and unlimited buffer size.
- The data packets are transmitted unchanged to the QMS and no data aggregation is performed.
- The radio links are unreliable, asymmetric and error-prone in nature.

3.2 QMS functionalities

3.2.1 Network initialization

The QMS acts as the coordinator of the IEEE 802.15.4 compliant IoT based WSN. The network operates in the non-beaconed mode of configuration. The PHY and MAC layers of IEEE 802.15.4 stack is initialized on all nodes in the network. The CIP is an integral part of network initialization.

3.2.2 Corona management

The Corona management is an alternate to the geographic routing scheme or WSN. The Corona Management is a flexible hierarchical routing which allows association with sibling node in case of void problem. The corona resembles virtual concentric circles centered around QMS with an assumption of uniform width of radius ‘r’. The radius ‘r’ represents the node’s transmission range and node can determine the relative distance to the sink based on the Corona Level (CL) it resides multiplied by ‘r’.

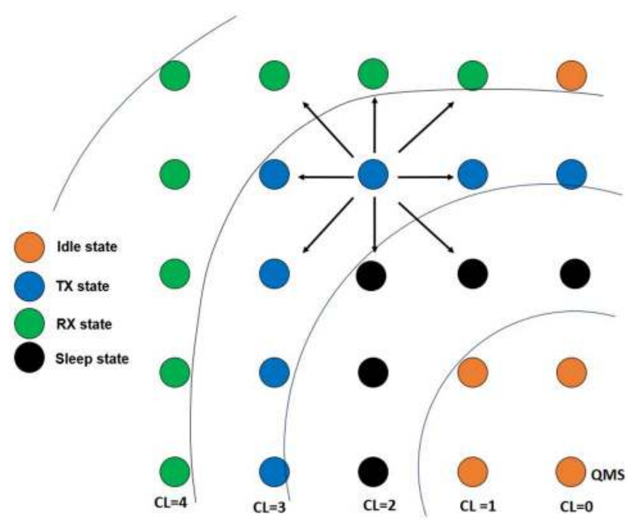

Fig. 3 Corona Interest Propagation (CIP) phase

Figure 3 displays the Corona Interest Propagation (CIP) phase. QMS initiates by broadcasting a CIP packet and sets a unique sequence number for the packet with CL set to 1. The one-hop neighborhood nodes upon receiving the CIP, learns its CL and repeats the broadcast in a level-based epoch manner after incrementing CL by 1 in the CIP packet.

In order to prevent broadcast storm and implosion via redundant receptions of the CIP from higher level nodes, nodes revert to sleep state after transmission of its CIP packet for a configurable time by invoking its power management module. This configurable time includes the typical frame transmission time, round trip delay and processing time in order to avoid redundant receptions from the next level nodes and minimize the energy cost in this dissemination process as modeled in the next section.

3.2.3 Mobility management

The QMS remains stationary during the data gathering phase in every round. The sojourn period for data collection depends on round duration that is determined based on the application requirement.

The mobility management invoked by the QMS imposes a path constrained mobility covering the two-dimensional deployment area. The QMS moves around the four corners of the deployment area in each round and then to the center of the deployment area. It is to be noted that the QMS does not send any topology updates during the movement. The QMS invokes the corona management module to restructure the corona levels of sensor nodes in WSN once it reaches the data gathering point. Figure 4 shows the possible movement patterns of QMS. This movement pattern could be looped till the life-time of the application.

3.2.4 Data gathering and upload via Wi-Fi/4G

Once the CIP phase is over, the QMS gathers the data from the distributed sensor nodes in multi-hop manner. This information driven sensor querying mechanism can be carried out by the QMS. The data gathered in each round are uploaded in the cloud infrastructure via Wi-Fi/4G internet of the end to end IoT system.

3.3 Sensor node functionalities

The SN can act as the source generating data packets, receiver of data traffic and relay (forwarder) to deliver packets to the sink in multi-hop manner. The functionalities involved are elaborated in the subsections.

3.3.1 Corona management

The Corona management from the SN point of view is used to learn and update its CL every round. This management module invokes the neighbor and power management modules for dynamic learning of neighbors after receiving the CIP along with its level information. The Power Management is invoked to switch the radio IEEE 802.15.4 compliant transceiver to sleep state or active state in order to avoid redundant reception of CIPs and achieve energy savings.

3.3.2 Neighborhood management

The SN maintains a Neighbor Table (NT) and stores the next hop Relay Nodes (RNs) for forwarding data packets. A Trust Value (*TV*) is mapped to every RN ($0 \le TV \le 1$). The *TV* denotes the stability of the time-varying link with respect to the RN. The *TV* is to keep track of trustworthy relays, which are updated on an instantaneous per-packet basis. When a SN learns about a new RN either via CIP or

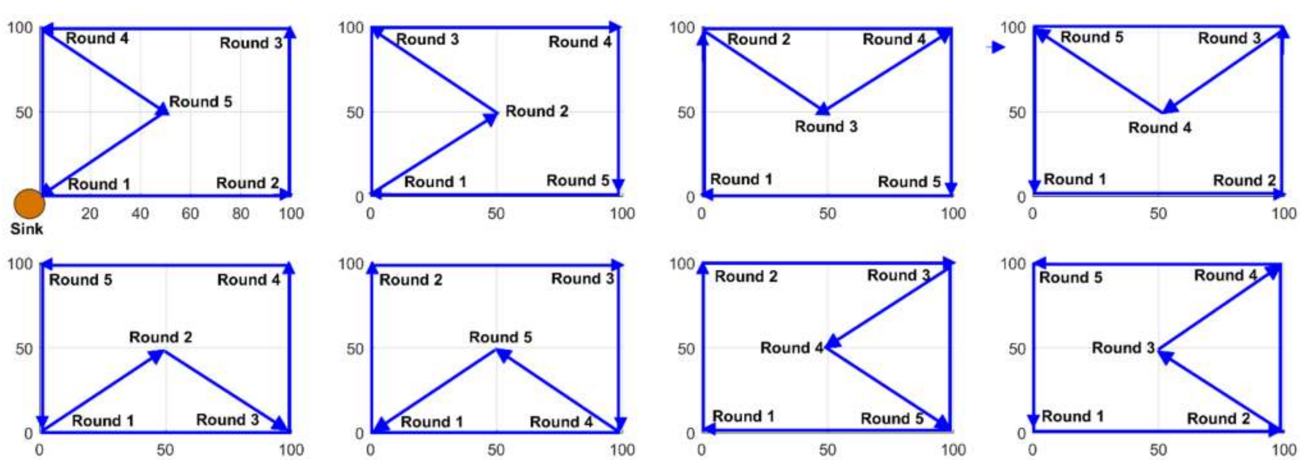

Fig. 4 Quasi mobile sink's mobility patterns

data-driven learning, it initializes its TV to 0.5 and adds an entry in NT. The instantaneous Link Quality Indicator (LQI) of the received packet via RN is also recorded to track the link asymmetry.

A RN will be classified as trust worthy if it's TV is $\geq$ 0.5. This threshold of 0.5 is set as the starting value, as it could either become trust worthy or non-trustworthy based on the status of future data packet(s) transmissions due to the time-varying link characteristics. For every successful transmission by the RN, the SN increases the TV of it in the NT by 10% of it's existing value and continues till it reaches the maximum value of 1. However, if link-level transmission error occurs with respect to the RN, the TV for that RN is penalized by 50% of it's existing value to make it non-trust worthy, and hence the RN with $TV < 0.5$ are classified as non-trust worthy. A non-trust worthy RN can become trust worthy again, if it wins the contention during opportunistic mode of transmission which will be further explained in next section on Data Forwarding management module.

3.3.3 Data acquisition & transmission

The SN as the source node acquisitions data via the interfaced sensors, packetizes the data which are fragmented as IEEE 802.15.4 frames for transmission. As the source of the data traffic, the SN invokes the Data Forwarding Management module to decide the mode of transmitting data packets.

3.3.4 Data forwarding management

The Data Forwarding Management module forms the core of the routing design to ensure robust data delivery and operate in an energy efficient manner.

- The SN as source of data traffic assigns a packet identifier (PACKET_ID) to each data packet and the SN address and packet identifier ensure unique packet generated in the network.
- For the initial packet transmission (PACKET_ID=1), SN adopts the contention based opportunistic forwarding mode.
- The source node operates in the opportunistic mode for its initial data packet transmission to cope with temporally varying wireless links and attempts to set up a virtual trustworthy, reliable backbone for subsequent transmissions in unicast mode to reach the sink in a multi-hop manner.
- The SN embeds only its CL information in the packet header and broadcasts the data packet.
- The RNs upon reception of the data packet determines whether they make progress by checking if the CL in the packet is greater than its own CL.
- The non-eligible nodes that makes no progress (in higher CL) can avoid further decoding the packet header and invoke the power management module to revert to sleep state till the next active cycle.
- Also, the RN whose residual energy is less than the minimum threshold will not participate in forwarding and revert to sleep state to recover its discharge.
- The eligible RNs computes its cross layered routing metrics on the fly in a fully distributed manner and invoke the fuzzy decision logic lookup table based on it's computed routing metrics (explained in detail in next section).
- These RNs determine it's priority order for dynamic holding time computation based on the fuzzy logic decision lookup table. The RN with the least holding time, whose timer expires first, contends to win the medium among other RNs to forward the data packet. In order to minimize high channel contention among RNs, these nodes incorporate a cross layered differentiated backoff MAC strategy depending on its priority order (explained in detail in next section).
- The RNs uses a priority queue to execute this timer-based coordination algorithm. This priority queue implementation consists of two items, the data packet and the scheduled transmission time for its transmission. The scheduled transmission time is computed based on the time of reception of the data packet and the dynamic holding time computed based on the fuzzy logic lookup table.
- A higher priority node will have an earlier scheduled transmission time. The scheduled transmission is aborted upon overhearing of the same packet transmitted by another RN. (explained in detail in next section).
- This online approach of data forwarding avoids the protocol overhead involved by the sender node in relay node(s) selection, prioritization, and adding the list of priority relay nodes in packet header before data transmission.
- This approach also facilitates to adapt to the time-varying lossy link characteristics and not rely on predefined relay candidates set or send periodic beacons to compute the priority relay candidates based on the estimation of routing metrics.
- Unlike the traditional Opportunistic routing scheme, to add the predefined list of priority wise sorted relay candidate nodes in the data packet before transmission leads to an increase in the packet header length. This further leads to an increase in the radio energy consumption of the sensor nodes (during transmission/reception) in the network. The proposed Hybrid OR protocol reduces the packet header length by adding only the corona level at which the sender node resides to reduce the energy consumption as shown in Fig. 5.
- The data forwarding process continues in the opportunistic mode for the initial data packet transfer till it reaches

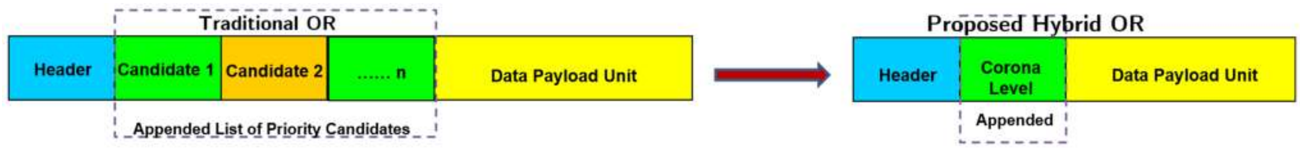

Fig. 5 Packet header—proposed hybrid OR

the sink, which sends an explicit Acknowledgement (ACK) to that RN.

- Meanwhile, the source node upon overhearing of the data packet forwarded by the RN within the max dynamic holding time, uses that as a passive ACK to transmit the subsequent packets in unicast mode, till a link-level transmission error occurs for the sender node to revert to opportunistic mode.
- The Data Forwarding module invokes the Neighbor management module to add the RN in the NT upon fresh learning of that RN with it's TV initialized to 0.5, or update the trust value of that RN if already exists in NT by increasing by 10% of it's existing value, and sets the ROUTE STATUS to active.
- For subsequent data packets transmission, the SN switches to unicast mode of forwarding if ROUTE STATUS is active based on the availability of trust-worthy relay node(s) in the NT. For every successful transmission by the trust-worthy RN based on the MAC level acknowledgment, the Neighbor management module updates it's TV accordingly.
- If multiple trustworthy RNs exist for SN, the RN with the maximum trust value in NT is chosen for transmission (and its reverse LQI beyond threshold for link asymmetry).
- The time-varying error-prone radio links can lead to transmission(s) error during unicast transmission and the continuous retry attempts at MAC layer should be minimized to reduce the energy wastage.Hence, the proposed hybrid mode of routing operation exploits the advantage by switching to opportunistic mode during link-level transmission error for achieving reliability and revert to traditional unicast mode during stable wireless links for achieving energy efficiency.
- If a link-level transmission error occurs in any subsequent unicast transmission due to the lossy links, the ROUTE STATUS is set to FAILED and SN switches to opportunistic mode for forwarding the data packet to ensure reliable data delivery and avoid energy wastage due to MAC-level retransmissions.
- The forwarding region is confined to RNs belonging to the lower or same corona level than the SN. The node in the same corona level is assigned the least priority order in the worst case to avoid the void issue or node failure in the lower level. In order to minimize the duplicate packet transmissions due to the non-overhearing of forwarded data packet because of hidden terminals, the hybrid mode of forwarding combats the drawbacks of the timer-based contention scheme despite erroneous wireless links.

3.3.5 Fuzzy metrics computation module

The eligible RN_i, (where i ∈ SN's neighbors) upon reception of broadcast data packet, computes its priority order based on following crisp inputs

- Instantaneous Link Quality Indicator (LQI) of the received packet,
- Trust Degree of RN_i i.e degree of RN_i containing trust worthy relays in its NT,
- Corona Level of RN_i.

The fuzzification step involves the conversion of these crisp inputs into the fuzzy set.

The normalized Link Quality LQI_{norm} is computed as per Eqn.1.

$$LQI_{norm} = \begin{cases} HIGH & \text{if } LQI_{(SN,RN_i)} <= LQI_L \\ MED & \text{if } LQI_L < LQI_{(SN,RN_i)} < LQI_H \\ LOW & \text{if } LQI_{(SN,RN_i)} >= LQI_H \end{cases} \quad (1)$$

where,

- LQI_{norm} is the normalized LQI,
- $LQI_{(SN,RN_i)}$ is the instantaneous LQI of received packet between the Sender Node (SN) and i^{th} relay node,
- LQI_L is the lower threshold of LQI,
- LQI_H is the higher threshold of LQI,
- LQI_{max} is the maximum LQI value.

Let $T_{deg}(RN_i)$ represent the trust degree of relay node RN_i having trust worthy relay nodes of atleast $\frac{1}{2}$. The fuzzy set mapping $deg(RN_i)$ is based on Eq. 2.

$$deg(RN_i) = \begin{cases} HIGH & \text{if } T_{deg}(RN_i) > 2 \\ MED & \text{if } 1 <= T_{deg}(RN_i) <= 2 \\ LOW & \text{if } T_{deg}(RN_i) = 0 \end{cases} \quad (2)$$

The relay nodes with $T_{deg}(RN_i) > 0$ will only participate in timer based contention.

The rule base for fuzzy decision logic used by eligible relay nodes is given in the Table 2.

In case of no relay nodes in lower CL i.e void problem, the nodes at same CL will have the lowest priority order with value 7. The defuzzification step involves determining the RN_i's priority order i.e crisp output based on the match in the fuzzy decision logic table.

$$T_{DH}(RN_i) = (PriorityOrder - 1) * T + \tau \tag{3}$$

where,

- $T_{DH}(RN_i)$ is the computed Dynamic Holding Time value of i^{th} trust-worthy relay node of SN, where $i \in T_{deg}(SN)$,
- $T_{deg}(SN)$ is the number of trust worthy relay candidates for Sender Node (SN),
- T is the predefined holding time,
- τ is the random delay factor between $[\tau_{min}, \tau_{max}]$ such that
- $T_{DH}(RN_j) < T_{DH}(RN_{j+1})$, j and $j+1$ are priority order of the trust-worthy RNs.

The eligible node with the least holding time whose timer expires first in order to win contention incorporates a differentiated Back-off strategy depending on the priority order as shown in Table 2. In a fully distributed, online decision making for holding time computation, the challenge that can arise are tie in eligible RNs with same priority order and also RNs choosing same back-off exponent as per the default IEEE 802.15.4 standard. In order to minimize high channel contention and ensure proper timer cancellation, the proposed design augments a random delay factor to the holding time computation and incorporates a differentiated back-off exponent depending on priority order.

The differentiated Back-off Exponent (BE) is shown in the Table 2. The RN_i with the highest priority order is assigned a shorter BE and has the highest chance to win the contention, if multiple RN_i exists. RN_i initializes the BE value to minBE and retries till maxBE if channel is busy for maximum number of backoff times (maxCSMABackoffs) before discarding as Channel Access Failure (CAF). If RN_i detects Clear Channel Assessment (CCA), then transmits its data packet. If RN_i receives the same packet that it intends to forward, it discards the packet.

Hence in the proposed hybrid routing design, the priority wise differentiated back off mechanism is implemented among the eligible relay candidate nodes during the opportunistic mode. This mechanism minimizes the high channel contention and thereby collision among the relay candidates since it can further lead to energy wastage. The design switches and continues further in the unicast mode of operation to the chosen relay node(s) till link(s) are stable to gain energy savings and avoid high channel contention by sensor nodes in the network.

Table 2 Fuzzy decision logic for RN

LQI_{norm}	$\deg(\text{RN}_i)$	Priority order	minBE	maxBE
HIGH	HIGH	1	2	4
HIGH	MED	2	3	5
MED	HIGH	3	4	6
MED	MED	4	5	7
LOW	HIGH	5	6	8
LOW	MED	6	7	9

3.3.6 Power management

The power management module in every SN is to select the transmission power level of the IEEE 802.15.4 compliant radio transceiver. The fixed transmission power level is chosen based on range test measurements in the environment of interest. The radio is either in active, idle or sleep states of operation. The non-eligible RN_i can revert to sleep state till the next active cycle to achieve energy savings. The SN during CIP, can revert to sleep state till next active cycle after transmitting its CIP packet to avoid energy-wastage. The reduced protocol overhead via data driven routing and eligible RN_i in idle mode of operation minimizes the energy-wastage in the network.

4 Mathematical analysis

4.1 Energy cost modeling of CIP phase (Corona Management)

The total energy cost involved in the CIP in the network can be modeled as:

Let E_{tx} be the transmission cost involved in the transmission of CIP Packet.

Let E_{rx} be the reception cost for receiving the CIP packet.

Let $\mathcal{N}(u)$ denote the open neighbourhood of u, $u \in V(G)$,

Let v be the potential parents of a sensor node u, where $v \in \mathcal{N}(u) \cap CL(i-1)$,

if $u \in CL(i)$ and i is the corona level at which u resides as shown in Fig. 6.

Every node in the network at $CL(i)$ transmits CIP only once upon reception of the CIP from neighbourhood nodes in $CL(i-1)$.

The reception cost for every node at $CL(i)$ includes only nodes from $CL(i-1)$ and not from $CL(i+1)$, as the node's radio transceiver in $CL(i)$ is put to sleep state after

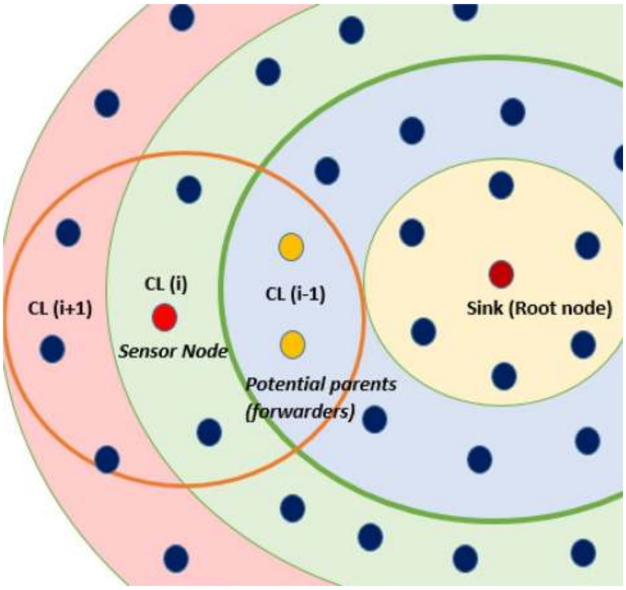

Fig. 6 CIP reception cost from potential parents

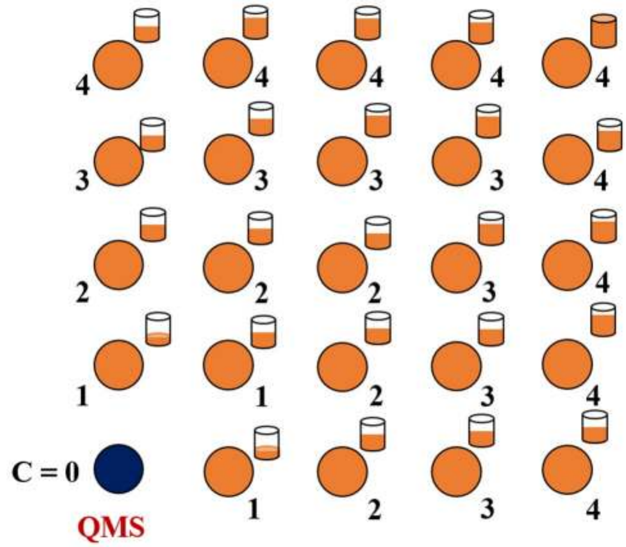

Fig. 7 QMS—energy dissipation modeling (Round 1)

it completes it's CIP transmission to avoid reception from nodes in $CL(i+1)$.

Per node (u)'s Energy Cost involved in disseminating CIP packet is as per Eq. 4.

$$EC(u) = E_{tx} + |\mathcal{N}(u) \cap CL(i-1)| * E_{rx} \tag{4}$$

- where $|\mathcal{N}(u) \cap CL(i-1)|$ is the number of potential parents of u for reception cost computation.

In case of non-uniform deployment of nodes, the Total Energy Cost involved in disseminating CIP throughout the network is as per Eq. 5.

$$TEC \leq N * E_{tx} + N * mE_{rx}, \tag{5}$$

- where, $N = |V|$ is the number of nodes in the network,
- $m = max\{|\mathcal{N}(u) \cap CL(i-1)| : u \in V(G)\}$,

As $m < N$, the significant energy cost is in higher order term $N * mE_{rx}$ for larger values of N. Hence $TEC < N^2$ as it minimizes the total energy cost in the CIP Phase, unlike the traditional flooding process with the problem of implosion.

4.2 Maximum energy dissipation modeling using QMS

Th energy dissipation by Sensor Nodes (SNs) is modeled and maximum energy dissipation is analyzed using QMS model and compared using Static Sink (SS) model. Figure 7 represents WSN for modeling energy dissipation.

Let N be the set of all sensor nodes partitioned into non-empty corona subsets $C_1, C_2, C_3 \dots C_n$ in such a way satisfying

$N = C_1 \cup C_2 \cup C_3 \cup \dots \cup C_n$ and for $i \neq j, C_i \cap C_j = \emptyset$.

C_i comprises the subset of nodes at the i^{th} corona level with respect to the QMS.

The QMS sets up the corona levels in the WSN and the lowest level ideally is the QMS itself i.e $C_0 = QMS$.

The corona width C_i is assumed to be of uniform width of radius R centered with respect to C_0.

The highest level or depth of the corona C_n comprises only the leaf nodes that transmits at a fixed rate in each round.

The nodes in previous corona level C_{n-1} would transmit not only its own data packets generated by it but in addition forwards the packets it receives from leaf nodes in C_n.

- The notion of Layers is used and comprises of several coronas w.r.to QMS.
- Each layer is of radius 'i' denoted as L_i with $L_i = C_1 \cup \dots \cup C_i$ $(i \in n)$.
- The number of nodes in each corona level is $c_i = |C_i|$,
- The number of nodes till Layer 'i' is $l_i = |L_i|$,
- The energy spent for transmitting an IEEE 802.15.4 payload frame be E_{tx} using fixed transmit power level P_t,
- The energy spent for receiving an IEEE 802.15.4 payload frame be E_{rx},
- The total energy spent per node for transmitting 'k' packets at a fixed rate at end of each round is kE_{tx}
- The total energy spent per node for receiving 'k' packets at end of each round is kE_{rx}

$$TE_i = \left\{ \frac{N - l_i}{c_i} \right\} kE_{rx} + \left\{ \frac{N - l_i + c_i}{c_i} \right\} kE_{tx} \tag{6}$$

where TE_i represents the total energy dissipated by nodes belonging to corona level C_i during each round as per Eq. 6 and this value represents the lower bound on energy spent for reception and transmission of packets by nodes belonging to the *ith* corona level.

$N - l_i$ represents the total number of nodes outside L_i that generates the data packets and received by the set of SNs in corona level C_i in each round. Hence, the nodes in C_i will need to forward packets generated by $N - l_i + c_i$ nodes in each round, comprising the total packets received from outer corona levels in addition to its own data packets generated by c_i nodes. In the best case, the load is distributed across all nodes in C_i to achieve energy balance for transmitting and receiving packets. This is represented by c_i factor as divisor.

It is evident that the nodes belonging to subset C_1 and residing in first corona level that are one hop away from the QMS, consumes the maximum energy among all the nodes residing in other corona levels with respect to QMS position. Hence, $max(TE_1, TE_2 \ldots TE_{n-1}) = TE_1$.

If the sink remains in the same static position throughout the lifetime of application, i.e with SS model at the end of the 5*th* round, the nodes that are one-hop away from the sink would have drained excessive energy and total energy dissipation can be expressed as in Eq. 7.

$$TE_1^{SS} = \sum_{n=1}^{5} \left\{ \left\{ \frac{N - l_1}{c_1} \right\} kE_{rx} + \left\{ \frac{N - l_1 + c_1}{c_1} \right\} kE_{tx} \right\}. \tag{7}$$

However, in the case of QMS model, the sink in every round reaches every corner of the deployment zone and also to the center of the deployment zone. This prevents the excessive energy drain among the sensor nodes, as the nodes that are in the sink's neighbourhood rotates in every round. Hence, at the end of the 5*th* round, the nodes that were one-hop away from sink in the first round would now in total have spent only as per Eq. 8.

$$TE_1^{QMS} = TE_1 + TE_{\lceil \frac{n}{2} \rceil} + 2TE_{n-2} + TE_{n-1} \text{ in the worst case,} \tag{8}$$

It is clearly evident that $TE_1^{QMS} < TE_1^{SS}$, and the energy dissipation is near uniform unlike the SS model. The QMS model facilitates to achieve energy efficient operation by preventing pre-mature death of nodes in hot spot region with respect to the sink and ensure long term sustainable operation and scalability of WSN.

4.2.1 Analysis of end to end delivery probability

Figure 8 shows the dynamic graph and assume the link delivery probability from Sender (S) to relay nodes are known, where P_{RN_1}, P_{RN_2} … $P_{RN_{T_{deg(S)}}}$ represent the link delivery probability from S to each of its relay nodes and $P_{RN_i} \neq 1$ The data packet needs to travel 'n' hops to reach the QMS. In opportunistic mode of forwarding, the probability that a transmission from S reaches the root node D (i.e QMS) via 'n' number of hops is

$$P_{OR} = \left(1 - \left(1 - P_{RN_1}\right) * \left(1 - P_{RN_2}\right) * \left(1 - P_{RN_3}\right) \ldots * \left(1 - P_{RN_{Tdeg(S)}}\right)\right)^n \tag{9}$$

In unicast mode of forwarding, the probability that a transmission from S reaches the root node D via 'n' hops by choosing the best relay node in each hop is

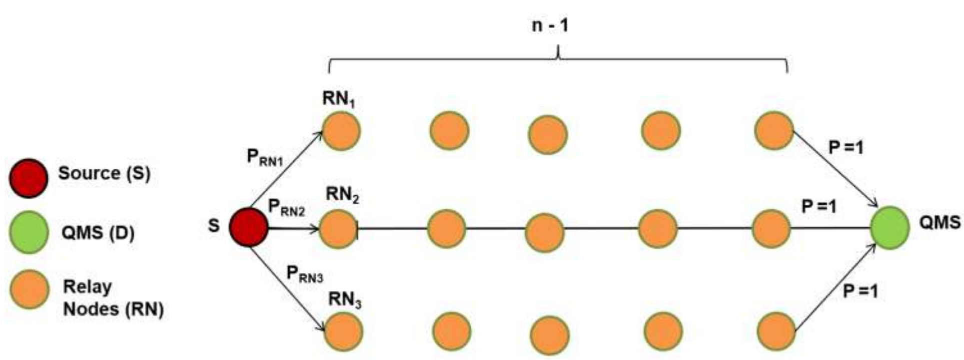

Fig. 8 Analysis of end to end delivery probability

$$P_{UR} = \left(1 - \left(1 - P_{RN_i}\right)\right)^n \tag{10}$$

It is evident that opportunistic mode of forwarding has a higher delivery probability i.e $P_{OR} > P_{UR}$. The fully opportunistic mode of forwarding approach using timer-based contention can achieve high delivery probability. However, the energy cost incurred due to duplicate transmissions if not properly coordinated or due to non-overhearing of already forwarded packet need to be minimized. The fully unicast mode of forwarding leads to poor delivery rate for large scale WSN. The proposed algorithm operates in a hybrid manner in order to achieve robust end to end delivery rate and reduce the overall energy cost.

5 Simulation results and discussion

The proposed routing algorithm with QMS support is implemented using Network Simulator (NS2) (Issariyakul and Hossain 2012). IEEE 802.15.4 PHY and MAC support layers for low power and low data rate radio is configured and used for evaluation. The performance metrics evaluated are as follows:

- *End to End Packet Delivery Ratio (PDR)* calculates the ratio of total successfully received packets by the destination to the total transmitted packets by the source node(s).
- *Maximum Energy Dissipation* (E_{max}) metric analyzes the distribution of energy dissipation of sensor nodes in WSN and determines the maximum dissipation value at the end of simulation. The energy dissipation per node is calculated as the difference between its initial available energy and remaining energy at the end of simulation period.
- *Average Energy Consumed per node* (E_{avg}) is calculated based on ratio of total energy consumed by all nodes in the WSN to the number of nodes at the end of simulation period.
- *Normalization Energy Consumption* metric is the energy consumed for delivery of data on per-packet basis. This is based on the ratio of total energy consumed by all nodes in the WSN to successfully deliver the total received packets at the destination. This is calculated to analyze the protocol overhead involved that increases the normalized energy consumption.

5.1 Simulation parameters and configuration

The configuration parameters set in NS2 is shown in Table 3. NS2 supports models to simulate link-level errors, radio signal propagation behavior, and radio transceiver's energy consumption. Two ray ground reflection model is linked with the error model and configured to simulate the error-prone

Table 3 Simulation parameters and configuration

Network parameter	Parameter value
IEEE 802.15.4 PHY parameters	
Frequency of operation	2.4 GHz
Transmission power level	0 dBm (1mW)
Antenna height	0.03125 m
Antenna configuration	Omnidirectional antenna
Radio propagation model	Two Ray Ground Reflection
Error model	Uniform distribution
Error rate (in units of packets)	1–50 % (Link Level errors)
Receiver sensitivity	– 110 dBm
Power spent per packet for transmission/reception	0.02955 W/0.0255 W (Ahmed 2013)
IEEE 802.15.4 MAC parameters	
minBE, maxBE	Default 3, 5 (Refer Table 2 for opportunistic mode)
maxCSMABackoffs	7
Mode of operation	Unslotted CSMA/CA—Non Beaconed
Routing parameters	
Holding time (T)	5 ms
Transport layer parameters	
Transport protocol	User Datagram Protocol (UDP)
Application layer parameters	
Application traffic	Constant Bit Rate (CBR)
Packet size	70 bytes
Packet rate	1–10 packets /s

wireless links. The energy model in NS2 models the radio energy consumption of the sensor node based on the state of the operation, i.e., receive, transmit, idle and sleep states.

- The Energy consumed by the sensor nodes is calculated based on the time the node spent in that state, the current drawn in that state, and the node's attached supply voltage.
- Energy consumed for transmission per packet is the power consumed by the radio transceiver during the transmit state (Joules). It depends on the length of the packet to transmit i.e., the packet's transmit time.
- Energy spent on reception per packet is the power consumed to receive the data packet (Joules). The power consumed is calculated based on the current drawn during the receive state and sensor node's attached supply voltage.

Figure 9 shows the simulation scenario for fixed network size of 121 nodes uniformly deployed in a regular grid manner with a spacing of 10m between adjacent nodes and field size of $100 \times 100\text{m}^2$.

The link-level error rate and traffic sources are increased in the simulation runs to evaluate the protocol performance.

5.2 Impact of increase in traffic sources

The proposed joint routing design with QMS model is compared with Static Sink (SS) and Uncontrolled Mobility Model based Sink (UMM-S). The UMM-S adopts random waypoint mobility pattern with pause time equal to duration of one round and periodic topology updates by mobile sink. In UMM-S model, sink moves in random speed between minimum and maximum speed towards randomly chosen destination point in the deployment area and sojourns for a fixed pause time. The statistical mean results for UMM-S model after 10 trials is computed and presented. The SS is placed at the periphery of the deployment area to analyze the scalability aspect of the routing design as it increases the average hop count to reach the sink.

5.2.1 PDR versus traffic sources

It is evident from Fig. 10, that with increase in number of traffic sources transmitting at fixed rate at scheduled time intervals, the data packets generated by nodes at higher

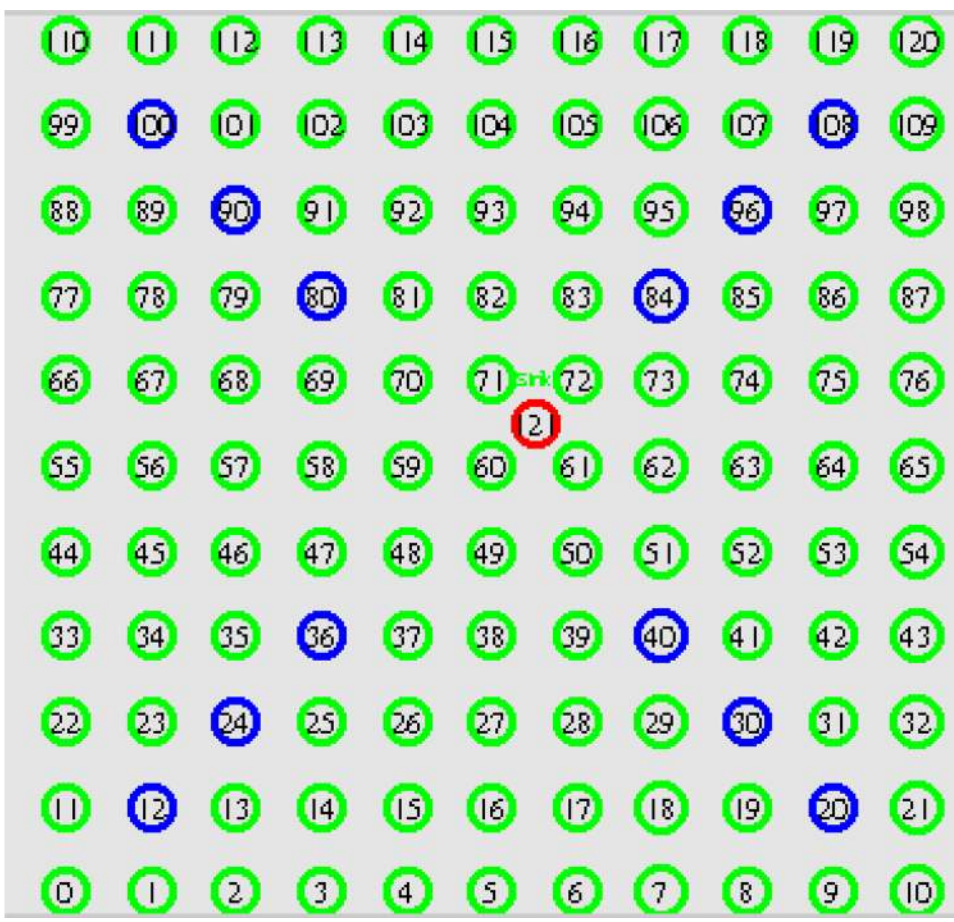

Fig. 9 Multiple Traffic Sources (at higher levels)—Blue denotes traffic sources, Red denotes Sink at grid center

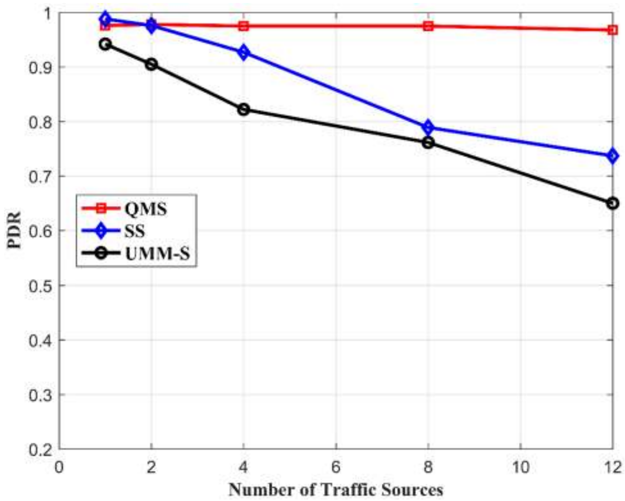

Fig. 10 PDR vs number of traffic sources

levels will need to travel more hops and with increase in traffic sources leads to high channel contention.

The packet error rate is fixed at 10% to simulate link-level errors. Due to hybrid OPSER design, the probability of successful data delivery increases. The QMS reduces the average hop count due to the number of rounds distributing the load across the network compared to the SS model. Due to increase in the number of hops, error-prone wireless medium and high channel contention, the UMM-S model with random mobility pattern incurs unbalanced topology updates and hence comparatively degrades in PDR with increase in number of traffic sources.

5.2.2 Average energy consumption vs Traffic sources

Figure 11 shows the average energy consumed per node is comparatively minimized using the QMS model as the load is distributed in the network due to the sink's placement covering the deployment area. The average reduction in the hop count with reliable forwarding via opportunistic mode minimized the drop rate and improves the energy consumption in the network. The SS model leads to hot spot region around the sink and uneven balance of energy consumption in the network. However, the hybrid routing design minimizes the energy consumption in the network with reliable routes despite error-prone wireless medium. The UMM-S model comparatively consumes higher average energy consumption per node due to the unbalanced topology updates.

5.2.3 Maximum energy dissipation (E_{max}) in the network

The sensor nodes battery power in the hot spot region drains rapidly with increase in number of traffic sources, as it need to relay all the data traffic generated by higher level nodes as well. The QMS model with the hybrid opportunistic forwarding design achieves load and energy balance in the network and prevent hot spot growth rapidly. The limited number of sojourn rounds and the sink's placement during the sojourn rounds minimizes the maximum energy dissipation in the network compared to the SS and UMM-S models.

Figure 12 clearly suggests that maximum energy dissipation by nodes in the network is significantly minimized in QMS model compared to the other sink models.

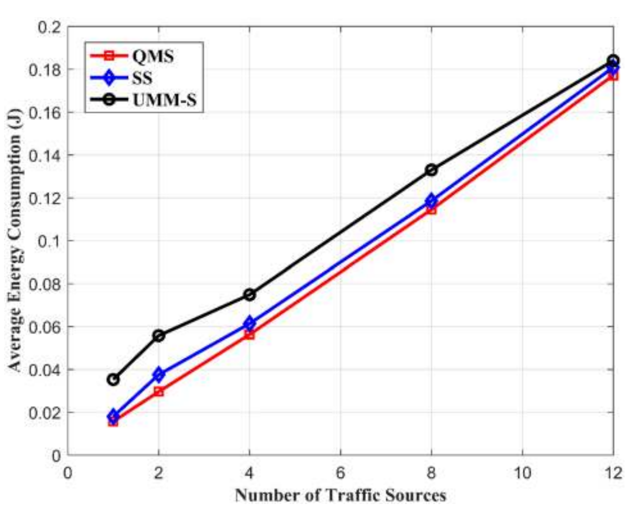

Fig. 11 Average energy consumption (J) vs Traffic sources

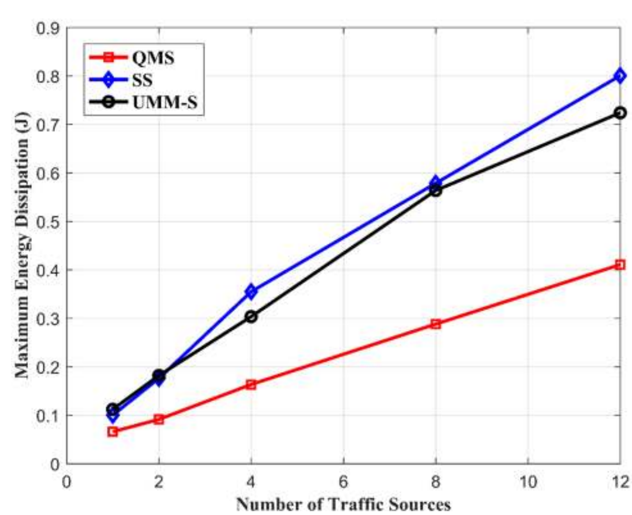

Fig. 12 E_{max}(J) versus Number of traffic sources

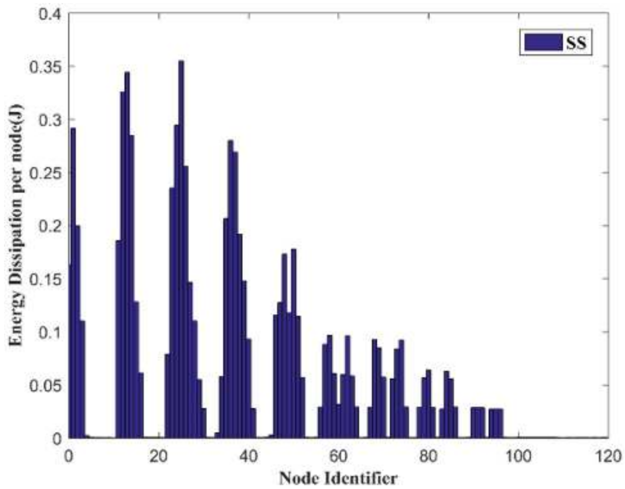

Fig. 13 Node wise energy dissipation analysis—SS model

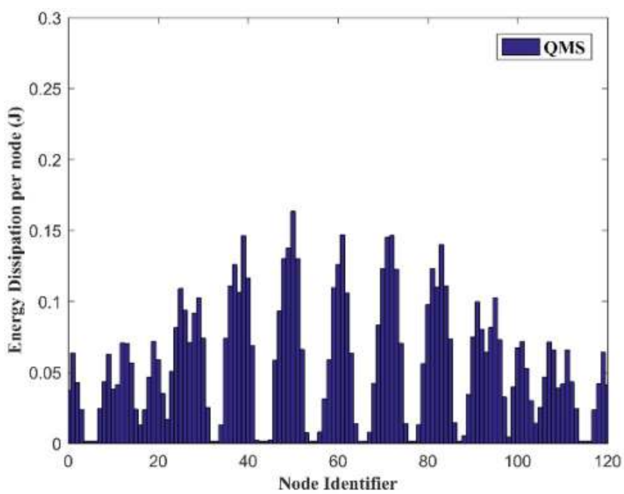

Fig. 14 Node wise energy dissipation analysis—QMS model

5.2.4 Energy dissipation analysis with static sink

Figure 13 displays the node wise energy dissipation using static sink for the fixed network size and error rate. It is clearly visible to see the maximum energy dissipation is towards the lower level nodes, the maximum recorded to be 0.36 J at the end of simulation period. This uneven node wise energy dissipation will lead to premature death of nodes in the neighborhood of sink halting the operations of the network. Hence, in addition to the energy efficient routing design, an efficient sink mobility model which balances the energy dissipation and topological updates will facilitate energy efficient operation in large-scale WSN.

5.2.5 Energy dissipation analysis with quasi mobile sink

Figure 14 displays the node wise energy dissipation using QMS model.

It is clearly evident that there is near uniform energy dissipation among all nodes in the network as there is load and energy balance in the network. Due to the sink placement in every sojourn round, the energy dissipation and topological updates are balanced appropriately in the network. The maximum energy dissipation is recorded to be 0.17 J per node which is reduced by two times compared to the SS model. This QMS model thus supplements for a scalable solution in addition to the proposed hybrid routing design.

5.3 Error rate analysis

This section presents the lossy-link modeling and performance evaluation of the proposed OPSER design for a fixed network size of 121 nodes with number of traffic sources set to 4 and packet rate configured to 5 packets per second.

5.3.1 PDR vs Packet error rate (PER)

To simulate extremely lossy links, the link-level error rate is increased and the performance of hybrid OPSER design is evaluated with sink models. It is evident from Fig. 15, that with increase in average hop count in large scale WSN and higher PER, joint OPSER design with QMS model achieves better PDR compared to other sink models.

The opportunistic mode of forwarding based on distributed timer coordination combats the high PER and thereby improves the PDR. The improved performance with joint QMS model is due to the average reduction in the hop count

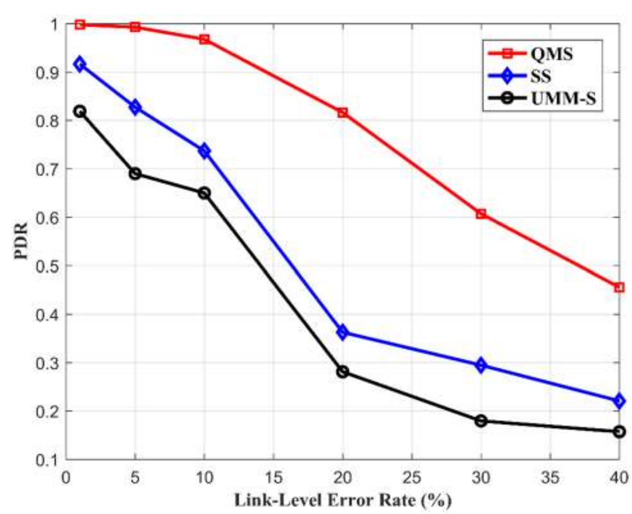

Fig. 15 PDR vs PER (link-level)

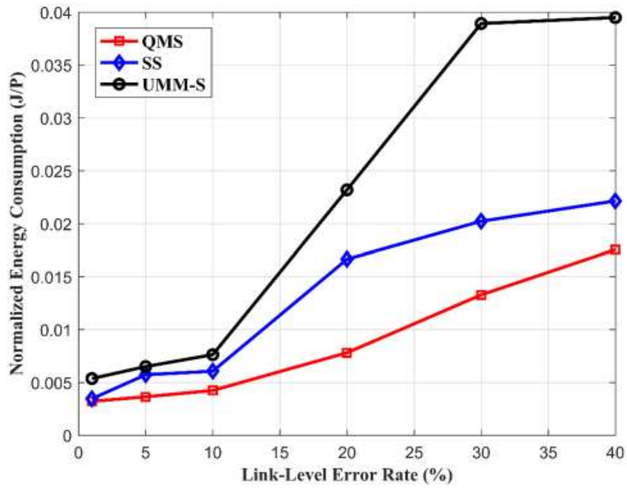

Fig. 16 Normalized energy consumption (J) vs PER (link-level)

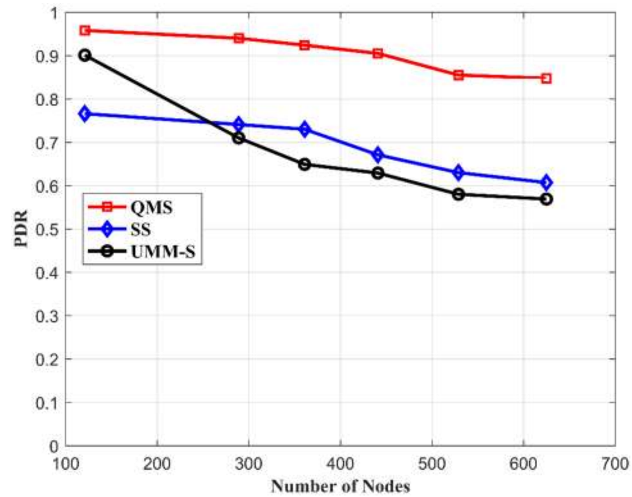

Fig. 17 PDR vs Number of nodes

and the trust based hybrid routing design. The protocol switches to unicast mode for successive transmissions to reduce the channel contention by relay nodes. Failure at link-level data relaying will revert to opportunistic mode, thereby improving the reliability of transmission and reduce MAC level retransmissions.

5.3.2 Normalized energy consumption vs PER

The normalized energy consumption is minimized in the proposed hybrid OPSER design as it's a data driven routing with reduced protocol overhead. The opportunistic mode of forwarding minimizes the energy wastage due to MAC level re-transmissions, despite high link-level error rate. The channel contention by the relay nodes and constant overhearing is minimized by switching to unicast mode of transmission for successive transmissions based on the trust-worthy relay node selection. Figure 16 shows that using joint QMS model, the normalized energy consumption is reduced significantly compared to other sink models as the hybrid design minimizes the energy wastage despite higher error rate and reduces the average hop count.

5.4 Scalability analysis

This subsection focuses on the scalability evaluation of the hybrid OPSER design with QMS by varying the network size and deployment area from 100×100 m^2 to 250×250 m^2. The link level PER is configured to 15% and number of traffic sources is fixed to 4 around the opposite peripheral ends of the deployment zone.

5.4.1 PDR vs Number of nodes

As the number of nodes are increased with increase in the deployment area, the number of corona levels increases from 10 till 25 which reflects the large scale simulation scenario.

The average hop count to reach the destination increases and the number of relay nodes gradually scales up. Despite presence of lossy links, the proposed hybrid OPSER achieves high packet delivery ratio as shown in Fig. 17 by exploiting the opportunistic mode of forwarding in the worst case and adopts unicast forwarding to the trust worthy relay(s) in the best case. It is also clearly evident that with QMS model, the OPSER shows better PDR in comparison with other sink models as it reduces the average hop count and balances the load and energy in the network.

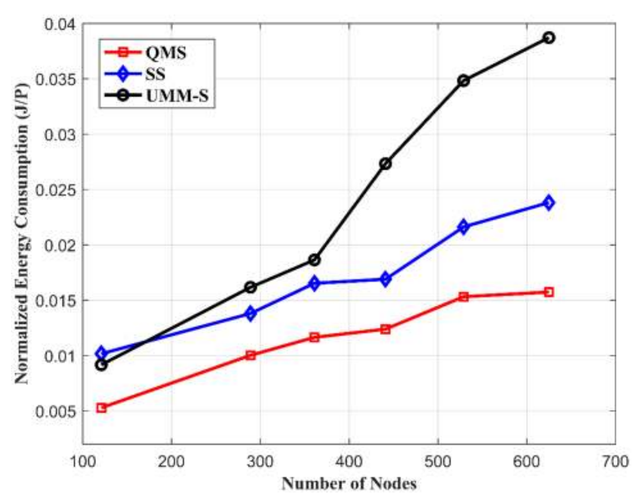

Fig. 18 Normalized energy consumption (J) vs Number of nodes

5.4.2 Normalized energy consumption vs Number of nodes

Figure 18 shows the normalized energy consumption per packet scales up as the number of nodes increases since number of relay nodes increases for reliable delivery of data.

The QMS model shows significant reduction in normalized energy consumption per packet compared to other sink mobility models since at the end of all rounds after the simulation period, the average hop count is reduced and it distributes the load and energy dissipation across the network compared to SS model. The UMM-S model incurs more extra overhead in energy consumption for unbalanced topology updates due to mobility.

5.5 Existing routing protocols comparison

The proposed hybrid OPSER design is compared with existing real time routing protocols such as RTLD, RTPC, POR (opportunistic routing protocol) and reactive AODV protocol. The original implementation of real time routing is configured to update the neighbor table every 180 s. For uniformity in comparison, all protocols are evaluated with static sink to analyze and evaluate the routing design. The field size is set to $100 \times 100\ \text{m}^2$, number of traffic sources is set to 4 and the static sink is placed at extreme diagonal end in the deployment area to increase the number of hops and path length. POR was originally built in NS2 with underlying 802.11 multi-rate extension. The multi-rate extension is not taken into account as modification in MAC layer is required and is evaluated with IEEE 802.15.4 PHY parameters. The link-level PER is set to 2% in the simulation.

5.5.1 PDR vs Packet rate

Figure 19 shows the proposed hybrid OPSER design achieves improved PDR in comparison with existing routing protocols with increase in packet rate by the traffic sources. The robustness of the proposed routing design to combat the error-prone radio links via hybrid mode of forwarding has lead to improved PDR compared to other protocols. The distributed on the fly relay node selection based on LQI, trust degree, residual energy and corona level with differentiated backoff strategy improved the reliable delivery of data. The unicast mode of transmission until link level transmission error for successive transmissions reduced the channel contention among relay nodes with increase in packet rate. However, the purely unicast driven real-time routing designs RTLD, RTPC, AODV degrades in performance with increase in packet rate in error-prone, large scale WSN.

Despite multiples metrics such as Packet Reception Rate (PRR), packet velocity and residual energy in RTLD, it is not opportunistic in design to cope with instant dynamics of time-varying links. The link-level errors will incur route request and replies among relay nodes leading to high channel contention and collision in IEEE 802.15.4 network. POR is a beacon based OR scheme with periodic hello packets exchange which incurs more control overhead and channel contention with increase in packet rate among traffic sources.

5.5.2 Average energy consumed vs Packet rate

Figure 20 shows the average energy consumed per node in the network with increase in packet rate. The total traffic load generated by each traffic source is fixed in the simulation period. The proposed hybrid routing design shows a significant reduction in the average energy consumed per node

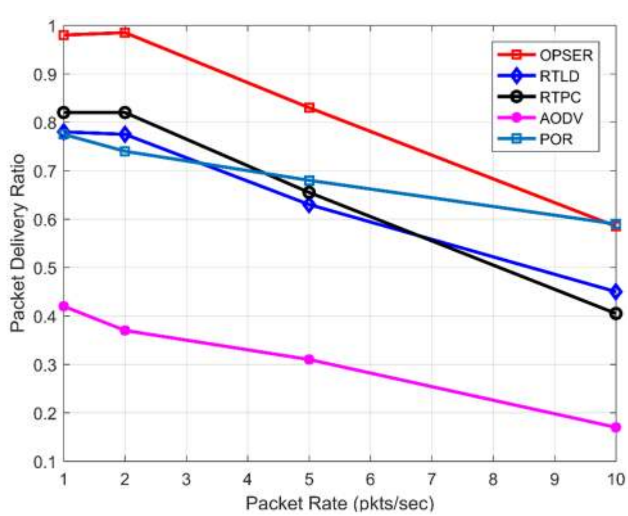

Fig. 19 PDR vs Packet rate (pkts/s)

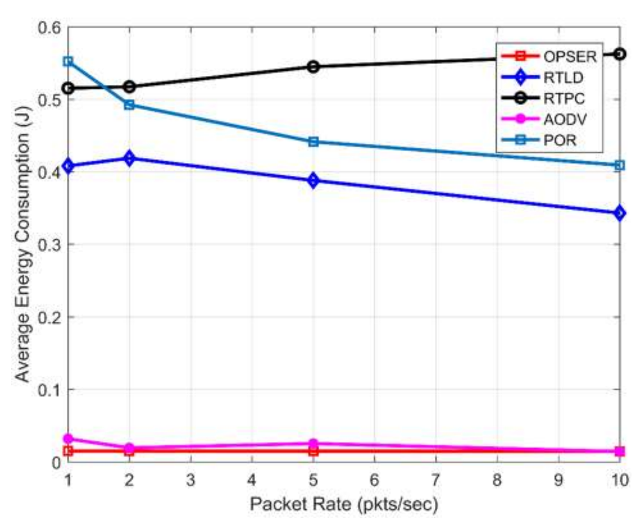

Fig. 20 Average energy consumption (J) vs Packet rate (pkts/sec)

as the protocol overhead is minimized due to the data-driven routing mechanism. Unlike the proactive routing schemes that involve the periodic beaconing by the sensor nodes for neighborhood management, routing metrics estimation, and also the neighbor table exchanges increase the burden on the node's battery consumption. This proposed routing design avoids table exchanges and periodic beaconing by sensor nodes and thereby minimized the average energy consumption in the network via the sink initiated corona framework driven routing approach. Also, unlike the reactive routing scheme, where sensor nodes expend energy by flooding route request(s) and route replies across the network, the proposed design minimized the average energy consumption via the hybrid opportunistic cross-layered data-driven routing design.

The control overhead factors such as periodic hello beacons, route requests, route replies and increase in packet header length to accommodate the list of priority relays are avoided in this design compared to the proactive POR, RTLD, RTPC and reactive AODV protocols. The real time routing protocols such as RTLD, RTPC experience higher energy consumption due to route requests, replies by sender and forwarders incurring extra overhead. POR incurs more overhead with periodic hello packets leading to higher energy consumption and channel contention.

6 Conclusions and further work

This work proposed and implemented a joint hybrid OPSER design and path-constrained QMS for IoT based large scale, lossy WSN. The simulation results of hybrid OPSER design were validated in NS2 and found to achieve high end to end packet delivery ratio despite the high link level error rate, minimized the average energy consumed per sensor node and normalized energy consumption per packet on comparison with existing routing designs. The joint routing design with QMS achieves a successful packet delivery ratio of 84.75% till a maximum of 25 levels (625 nodes) characterized by 15% link-level error rate. Using the Static Sink, Hybrid OPSER achieves packet delivery ratio of 60.7% for the same configuration. The joint QMS path-constrained model supplemented the routing design to achieve a scalable solution, and effectively combats the hot-spot formation. The maximum energy dissipation in the network with joint QMS model is reduced by two times compared to the static sink.

The proposed design in its current form is limited to considering the link dynamics i.e lossy link behavior. The simulation was limited to static deployment of nodes and further would be extended to dynamic topology due to node mobility. The sensor nodes moving out of corona level would reset its level information and perform dynamic learning of corona level with minimal overhead. The proposed design can be extended for IPv6 based Routing Protocol for Lossy networks (RPL), since RPL does not exploit opportunism during packet forwarding and also the flexibility offered via the corona driven framework. The objective function for RPL parent selection could be multi-metrics and can be computed on the fly in a distributed manner.

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