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Review paper

A Review on Reliable Data Transport Protocols in Wireless Sensor Networks

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Abstract

Background and Objectives: Reliable data transmission and congestion control are considered as the transport layer primary functions in Wireless Sensor Networks (WSNs). WSNs are a specific category of wireless ad-hoc networks where their performance is highly affected by their characteristics and limitations. These limitations necessitate an effective data transport control in WSNs which considers quality of service (QoS), energy efficiency, and congestion control.
Methods: Congestion affects normal data transmission and ends in packet loss. Furthermore, wireless channels introduce packet loss because of high bit-error rate which wastes energy and affects reliability. The major problems regarding transport protocols in WSNs are congestion and reliability where the latter is classified and reviewed in the current paper.
Results: In this paper, reliable data transport protocols are classified as the traffic direction, the parameter the reliability focuses on, and loss detection, notification, and recovery. Traffic direction-based reliable data transport protocols can be upstream, downstream or bidirectional, however, the parameter-based ones can be packet-based, event-based or destination-based, the loss detection and notification-based ones can be ACK-based, NACK-based, ACK and NACK-based or SACK-based, and the loss recovery-based reliable data transport protocols can be E-2-E or H-by-H. Thereafter, a comprehensive review of different reliable data transport protocols in wireless sensor networks is presented. Also, different performance metrics are used to compare these schemes.
Conclusion: In this paper, reliable data transport protocols in WSNs are classified, reviewed and compared using different performance metrics. Finally, the current work attempts to provide specific directives to design and develop novel reliable data transport protocols in wireless sensor networks.

Introduction

A WSN is a collection of sensor nodes which is distributed and organized in a network to monitor different environmental or physical conditions to estimate the monitored system state. WSNs gather the required information by smart environment as home, buildings, industrial sites, and utilities. In WSNs, there exist one or more sinks and many sensors which are deployed on a physical area. The unique characteristics in WSNs can be listed as resource limitations, special traffic characteristics and the multi-hop tree topology utilization [1]. Although, the Transmission Control Protocol (TCP) [2] and User Datagram Protocol (UDP) [3] are considered as the most important transport protocols which are deployed in the Internet; they cannot be utilized in wireless sensor networks because of the throughput and energy efficiency constraints. There exists no interaction between UDP, TCP and the lower-layer protocols [4]. The major TCP drawback can be considered as the end-to-end (E-2-E) error control which is based on retransmissions, and also the Additive-Increase Multiplicative-Decrease (AIMD) [5] congestion control mechanisms which are not applicable in WSNs [6]. Moreover, since UDP is connectionless, it is not suggested in wireless sensor networks. Also, the lost datagrams can be recovered since there is no ACK mechanism in UDP [7].

Transport protocols are of paramount importance in wireless sensor networks since they offer congestion control, reliability, fairness and energy efficiency. There has been a vast amount of research to overcome the standard protocol limitations by introducing efficient transport protocols for wireless sensor networks. However, different mechanisms are used to transport data in wireless sensor networks. The data transport protocols are classified as the protocols that only support congestion control, the ones that only support reliability, and the protocols that support both congestion control and reliability [8]. The transport protocol enables E-2-E message transmission where message fragmentation is accomplished at the senders which are reassembled at the receivers. The transport protocol usually provides some functions as loss recovery, orderly transmission, QoS guarantee and congestion control. The major problem concerning transport protocols in WSNs is packet loss and congestion. In order to design an efficient data transport protocol for WSNs, the traffic characteristics, the application diversity, the topology, and the resource constraints shall be considered [8].

In this paper, reliable data transport protocols in WSNs are categorized and reviewed. Furthermore, different performance metrics are utilized to compare reliable data transport schemes in WSNs. Finally, future works are provided to design and develop new reliable data transport protocols in WSNs.

The remainder of this paper is as follows: First an overview of congestion algorithm in WSNs is presented, followed by the reliable data transport protocols and comparison of reliable data transport protocols. Finally, the paper is concluded and the future directions are provided.

Congestion Algorithm in WSNs

Congestion algorithms in wireless sensor networks are classified as congestion mitigation, congestion avoidance, and reliable data transmission [9]. Fig.1 shows the congestion algorithm in WSNs.

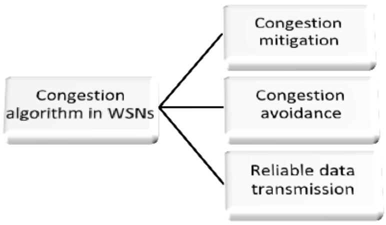

Fig. 1: Congestion algorithm in WSNs [9].

Congestion Mitigation

Congestion mitigation schemes take reactive actions in case congestion occurs in WSNs and aim to control it. MAC, network, and transport layer operations are used in the aforementioned schemes. Congestion mitigation algorithms are classified according to the way congestion is detected, the way other nodes are notified for this incident, and the way congestion is faced [9]. Fig.2 shows the congestion mitigation in WSNs.

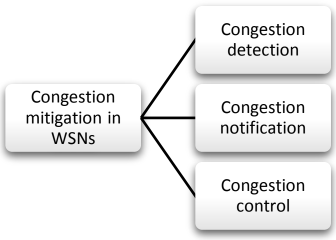

Fig. 2: Congestion mitigation in WSNs [9].

Congestion Detection

In WSNs, congestion detection is accomplished by one or more nodes towards the sink. There exist different metrics to detect congestion, i.e., packet loss, queue size, queue size and channel load, packet service time, packet service time and queue size, channel busyness ratio and throughput measurement, delay, scheduling time, reliability parameters and application fidelity [10], [11]. Fig. 3 shows the congestion detection metrics in WSNs.

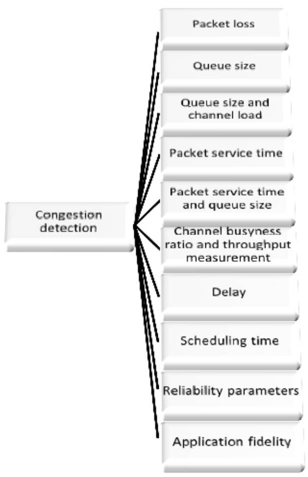

Fig. 3: Congestion detection in WSNs [10], [11].

Congestion Notification

Congestion notification is assessed after it is detected. In order to notify congestion, congestion information is transmitted in different ways. It can be notified either implicitly or explicitly across the WSN. In implicit method, by overhearing the sent data packets, congestion information is transmitted in the header of data packets [12]-[28], However, in explicit method, congested nodes broadcast separate control packets to notify their congestion status [29]. For congestion notification, implicit congestion notification is suggested to prevent extra load in the congested network. Fig. 4 shows the congestion notification in WSNs.

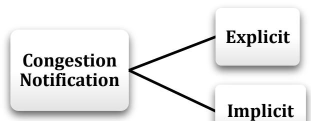

Fig. 4: Congestion notification in WSNs [1].

Congestion Control

Congestion control algorithms are listed under 13 categories [30], i.e. traffic control [31]-[34], resource control [35], traffic and resource control [36], fairness-based [37], priority-aware [38], end-to-end (E-2-E) or hop-by-hop (H-by-H) [31]-[34], energy efficient [39], reliability-based [12]-[29], [40]-[55], queue-assisted [31]-[34], centralized or distributed [31]-[34], generic or cross layer [56], content-aware [57], and soft computing-based congestion control schemes [58]. However, soft computing-based congestion control schemes [58] are listed as fuzzy logic-based congestion control schemes [59], game theory-based congestion control schemes [60], swarm intelligence-based congestion control schemes [61], learning automata-based congestion control schemes [62], and machine learning-based congestion control schemes [63]. Hop-by-hop congestion control schemes are also suggested, since end-to-end schemes end in error rate and latency increase and reduced responsiveness. Fig. 5 shows the congestion control classification in WSNs.

Congestion Avoidance

Congestion avoidance schemes are the algorithms which take action to prevent congestion occurrence. Congestion avoidance can be accomplished in different ways which are listed as follows:

A. Rate adjustment

It regulates the congested node transmission rate upon the reception of congestion notification. It can be either centralized or distributed. The centralized technique used in [14], [15], [17], [24] is more energy-efficient than the distributed one used in [12], [19], [20], [22], [27], however, congestion reduction in the distributed form is accomplished quicker than the centralized one.

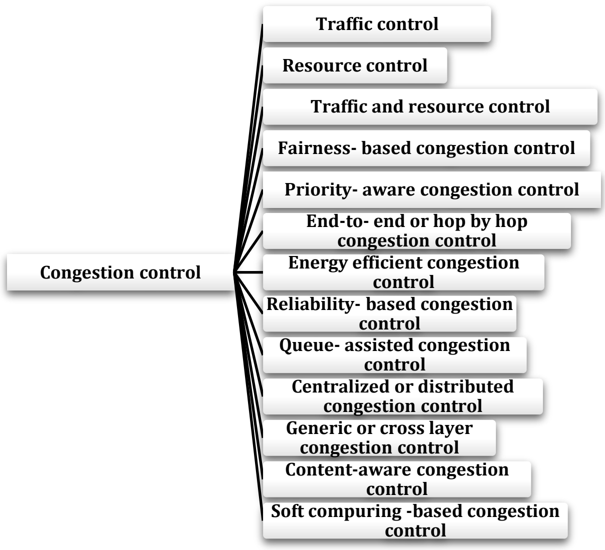

Fig. 5: Congestion control in WSNs [30].

Moreover, the rate adjustment schemes can be classified as simple or exact rate adjustment where in the former, congestion is notified by a single congestion notification bit, however, in the latter, and the neighbors' information adjusts the rate. The simple rate adjustment scheme can be simply classified as AIMD which is used in [12], [14], [17], [19] or Additive increase additive decrease (AIAD) as used in [24].

However, the exact form of rate adjustment can be simply classified based on the neighbors' information which can be either the acceptable data rate as in [27] or the congestion degree as in [64] or the delay parameter as in [15], [22].

B. Traffic redirection

In this scheme, the feedback information ends in avoiding the congested paths, and the outgoing traffic is dynamically allocated to the paths which are not congested. Both traffic redirection and rate adjustment are used in [12], [16].

C. Polite gossip policy

In this scheme, a summary of node data is broadcasted to the local nodes, however, in case identical data is heard from the neighbors, the broadcasting process will be politely suppressed. In case of hearing new data, the broadcast period will be shortened. On the other hand, in case of hearing old data, nodes will be updated using a part of the packet. This policy is rarely used and is suggested in [65]. Fig. 6 shows the congestion avoidance in WSNs.

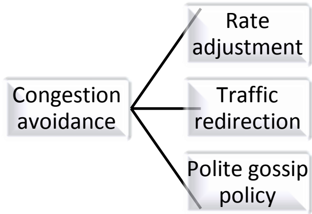

Fig. 6: Congestion avoidance in WSNs [12], [14], [65].

Reliable Data Transmission

Reliable data transport protocols are classified as the traffic direction, the parameter the reliability focuses on and loss detection, notification, and recovery.

A. Traffic direction-based reliable data transport protocols:

The traffic direction can be upstream [40]-[53], downstream [54]-[55] or bidirectional [20]. In upstream and downstream reliability, the successful delivery of dataflow traffic from sources to sink, and the successful delivery of control packets from sink to sources are satisfied, respectively. However, both direction reliability is guaranteed in bidirectional reliability.

B. Parameter-based reliable data transport protocols:

Reliability may focus on different parameters as packet, event or destination. In case it focuses on packet, the successful delivery of all packets to the destination which is of paramount importance in specific control applications is taken into account [12], [14], [18], [19], [21]-[24], [27]-[29], [41]-[47], [49]-[55]. However, if it relays on event, the successful event detection and the successful delivery of at least one packet in a sensor field is expected [13], [15]-[17], [20], [25], [26], [40], [48]. Packet-based reliability is more trustworthy comparing with the event-based one since it guarantees all information delivery. However, more energy is utilized in packet-based reliability comparing with the event-based one. So, adaptation to both parameters shall be considered in the protocol design regarding the targeted application. Also, destination-based reliability refers to the successful sending of message to the selected nodes or clusters in WSNs [55].

C. Loss detection and notification-based reliable data transport protocols:

In reliable data transport protocols, in case a packet is dropped, packet sequence numbers are used for packet loss detection. In this case, packet header is embedded with source identifier and the sequence number. The packet loss is notified using four types of feedbacks, namely, positive acknowledgements (ACK) [13], [18], [21], [26], [27], [29], [47], [49], [51], [53], negative acknowledgements (NACK) [19], [24], [28], [45], [46], [48], [50], [52], [54], [55], ACK and NACK [12], [14], [20], [43], and Selective ACK (SACK) [22], [51]. ACK can be either explicit (eACK) or implicit (iACK). In eACK, in case a packet is received, the corresponding node explicitly notifies the base station about the packets which are completely received. However, in iACK, in case of overhearing the neighbor forwarding a packet, the successful delivery of packet is assumed. Noted that a packet delivery is confirmed in iACK, however, a single or multiple packet delivery is confirmed in eACK. In NACK, the sender is explicitly notified about the packets which shall be retransmitted. In SACK, the last in-order received packets utilize a combination of explicit single or multiple ACK, however, other out of order received packets utilize multiple ACKs.

D. Loss recovery-based reliable data transport protocols:

In loss recovery, packet drops are repaired by packet retransmission.

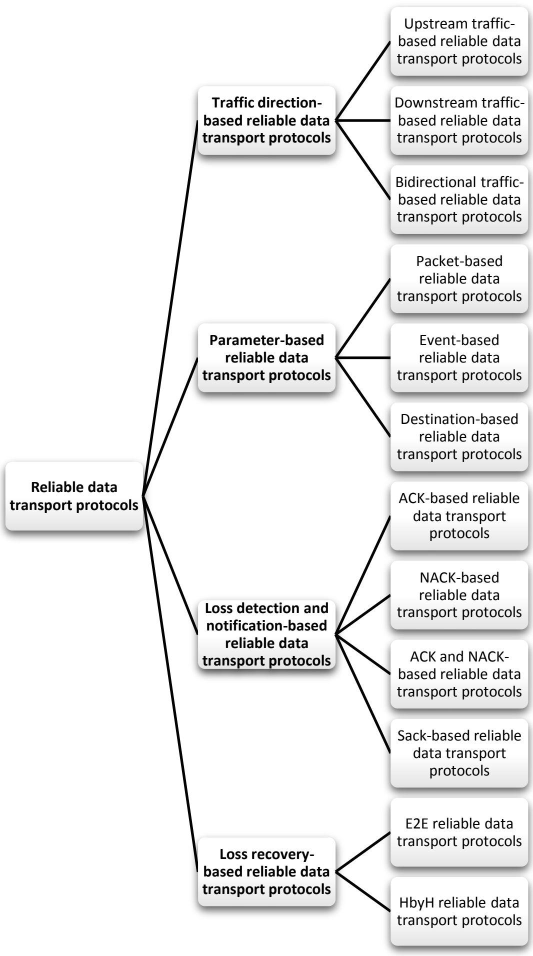

Fig.7: Reliable data transport protocol classification.

It can be classified as E-2-E [14], [12], [15], [17], [19]-[21], [24]-[26], [28], [29], [43], [44], [47], [49], [50], [52], [53] or H-by-H [13], [18], [22]-[24], [27], [40]-[42], [45], [46], [48], [51], [53], [54] where in the former, loss detection and notification is accomplished by the end points, however, in the latter, the packet information is cashed by the intermediate nodes. Noted that E-2-E techniques are not applicable in large networks because of consuming large amount of energy. However, H-by-H techniques consume less energy comparing with E-2-E ones since only two adjacent nodes are involved in loss recovery. But in H-by-H mechanisms more memory is needed. Fig. 7 shows the reliable data transport protocol classification. Congestion algorithm in WSNs is categorized as congestion mitigation, congestion avoidance, and reliable data transmission. First congestion mitigation is categorized as congestion detection, congestion notification and congestion control, thereafter, congestion avoidance and reliable data transmission are categorized.

Reliable Data Transport Protocols

In this section, some well-known reliable data transport protocols are summarized as traffic direction-based, parameter-based, loss detection and notification-based and loss recovery-based reliable data transport protocols [12]-[29], [40]-[55]:

Traffic Direction-based Reliable Data Transport Protocols

In this subsection, some well-known traffic direction-based reliable data transport protocols are categorized as upstream, downstream and bidirectional traffic-based reliable data transport protocols which are as follows:

Upstream Traffic-based Reliable Data Transport Protocols

Some well-known upstream traffic-based reliable data transport protocols are summarized as follows [40]-[53]:

A. Energy-efficient and Reliable Transport Protocol (ERTP)

ERTP [47] is presented for data streaming applications where data is transmitted from sensors to a sink in WSNs. In ERTP, the H-B-H iACK technique and the duplicate detection are both utilized to analyze the trade-off between E-2-E reliability and energy consumption. This protocol presents a technique to estimate the retransmission timeout. The retransmission timeout algorithm renders superior performance in terms of energy efficiency comparing with other schemes. In ERTP, the retransmission timeout is adaptively estimated for H-B-H iACK schemes in wireless sensor networks. ERTP is implemented in TinyOS for real world WSNs. The results confirm energy consumption reduction which makes lifespan extension possible.

B. Flush

Flush [19] is a reliable bulk data transport protocol for WSNs where E-2-E reliability, transfer time reduction, and network condition adaptation are obtained. In Flush, both rate control scheme and E-2-E ACKs are used which operate at each hop. In this protocol, congestion detection is accomplished based on buffer occupancy and link interference. Also, implicit congestion notification is used and the rate adjustment technique is utilized for congestion control. In this protocol, different real network topologies are used. Moreover, in case of varying network conditions, Flush is able to closely track or exceed the maximum goodput. It is a scalable protocol with an effective bandwidth which is much less than the rate achieved over a single hop. A simplified assumption considered in Flush is that the flows do not interfere with each other which is an important restriction in several WSN applications as volcanic or structural health monitoring where bulk data is collected.

C. Distributed Transport for Sensor Networks (DTSN)

DTSN [43] is an E-2-E reliable data transport protocol for converge cast and unicast communications in WSNs. In this scheme, the loss recovery process is controlled by source to minimize the data and control packet overhead. DTSN can detect in case all session packets are lost. Caching at intermediate nodes is suggested to make the transport reliable TCP-like model efficient. Reliability differentiation is gained by integrating the source partial buffering and caching at the intermediate nodes. DTSN is energy-efficient; however, it is not fair. Results confirm full and differentiation mechanism reliability in DTSN.

Downstream Traffic-based Reliable Data Transport Protocols

Some well-known downstream traffic-based reliable data transport protocols are summarized as follows [54], [55]:

A. Pump Slowly, Fetch Quickly (PSFQ)

PSFQ [54] is a H-by-H reliable data transport protocol which is both robust and scalable. In PSFQ, the data segment delivery is guaranteed and a loose delay bound is provided for delivery purpose. Moreover, it can operate in harsh environments. In PSFQ, pump, fetch and report operation are accomplished. In pump operation, the packet rate is controlled. A scheduling technique with two timers, namely, *Tmin* and *Tmax* is used in this operation where the former is considered as the minimum time that a node must wait before packet transmission to recover the missed packets and reduce the redundant broadcasts, however, the latter is considered as an upper bound of delay needed for packets to be received. The fetch operation is defined as the time where there exists a sequence number gap between the received packets in case the lost packet retransmission is requested from the neighbors. Finally, a feedback status is provided to users in the report operation.

Bidirectional Traffic-based Reliable Data Transport Protocols

Some well-known bidirectional traffic-based reliable data transport protocols are summarized as follows [20]:

A. Asymmetric and Reliable Transport (ART)

ART [20] is a reliable data transport protocol which can control congestion. The reliability direction in ART is both upstream and downstream. In ART, an E-2-E mechanism is utilized for loss recovery purpose. It is energy-efficient; however, fairness is not guaranteed in this protocol. In ART, the nodes are categorized as essential and nonessential nodes where the reliability is guaranteed for the essential ones.

Parameter-based Reliable Data Transport Protocols

In this subsection, some well-known parameter-based reliable data transport protocols are categorized as packet-based, event-based and destination-based reliable data transport protocols which are as follows:

Packet-based Reliable Data Transport Protocols

Some well-known packet-based reliable data transport protocols are summarized as follows [12], [14], [18], [19], [21]-[24], [27]-[29], [41]-[47], [49]-[55]:

A. Reliable Transport with Memory Consideration (RTMC)

RTMC [23] is considered as a H-by-H reliable and congestion control transport layer protocol for WSNs. In RTMC, the memory information is included in the packet header and the information is exchanged between the neighbors. In RTMC, the segment reliability of each link is guaranteed. In this protocol, congestion detection is accomplished based on memory overflow and implicit congestion notification is used. Also, the rate adjustment technique is utilized for congestion control. It is shown that in RTMC, the transport time and memory cost are reduced and throughput is maximized.

B. Congestion-Aware and Rate-Controlled Reliable Transport (CRRT)

CRRT [24] is a data transport protocol which mitigates congestion and guarantees reliability in WSNs. In CRRT, congestion avoidance is accomplished by a rate control scheme, and a reservation-based MAC retransmission mechanism is presented which ends in delivery ratio enhancement. In CRRT, both E-2-E and H-by-H mechanisms are utilized for loss recovery purpose. In this protocol, congestion detection is accomplished based on the packet rate and queue length and implicit congestion notification is used. Also, congestion is controlled by the sink and the rate adjustment technique is used. In this scheme, congestion avoidance is also used in order to avoid unnecessary packet drops.

C. Collaborative Transport Control Protocol (CTCP)

CTCP [29] is a reliable congestion control and data transport protocol for WSNs. CTCP performance is evaluated by the number of successfully received packets and energy consumption. Different CTCP features can be considered as the reliable packet delivery to sink, energy efficiency, congestion control and congestion loss distinguishment from the transmission error loss. In this protocol, congestion detection is accomplished based on buffer occupancy and the transmission error loss. Moreover, explicit congestion notification is used and the rate adjustment technique is utilized for congestion control. Also, reliability is gained and an E-2-E mechanism is utilized for loss recovery purpose.

D. Reliable Data Transport in Sensor Networks (RMST)

RMST [46] evaluates the reliability placement for data transport at different levels of protocol stack. In RMST, reliability is implemented in MAC, transport and the application layer. In RMST, MAC-level reliability is important for H-by-H error recovery, route discovery and maintenance. RMST is developed for in-network data processing. In this protocol, data delivery is guaranteed. Also, diffusion routing is addressed with the least control traffic.

E. Reliable Erasure-Coding Based Data Transfer Scheme (RDTS)

Reliability enhancement can be accomplished by retransmission and information redundancy [66], [67] where the former is not suggested in WSNs due to the limited sensor memory size, however, the latter is more energy efficient. Erasure coding can be considered as an efficient technique for information redundancy which is used in [44]. In reliable erasure-coding based data transfer scheme (RDTS) [44], H-by-H erasure coding is assessed so that each intermediate node can handle erasure coding and calculate the redundant packet number for the next hop. The network load is reduced in RDTS which extends network lifetime. Furthermore, H-by-H coding ends in low coding overhead. The results confirm that RDTS ends in less network load, less overhead and longer lifetime.

Event-based Reliable Data Transport Protocols

Some well-known event-based reliable data transport protocols are summarized as follows [13], [15]-[17], [20], [25], [26], [40], [48]:

A. Enhanced Event-to-Sink Reliable Transport (E^2SRT)

E^2SRT [25] enhances ESRT by resolving the overdemanding problem regarding the reliability issue. It also enhances ESRT in terms of energy efficiency. Moreover, E^2SRT renders superior performance in comparison with ESRT in terms of throughput, loss rate and latency. E^2SRT is robust to environmental changes. In this protocol, congestion detection is accomplished based on queue length, implicit congestion notification is used and rate adjustment is utilized for congestion control. Also, reliability is gained and event to sink mechanism is utilized for loss recovery purpose.

B. Loss-Tolerant Reliable Event Sensing (LTRES)

LTRES [26] is a reliable data transport protocol in WSNs which is specifically used to observe dynamic events. Also, LTRES renders superior performance in comparison with LSR in terms of packet transmission minimization and energy consumption reduction. In this protocol, congestion detection is accomplished based on link loss rate, implicit congestion notification is used and rate adjustment technique is utilized for congestion control. In LTRES, event-to-sink reliability is established for the event area rather than each node. It is implemented in WSNs in case of various reliability requirements.

C. Price Oriented Reliable Transport protocol (PORT)

PORT [16] is a data transport protocol which facilitates the sink to obtain reliability. In PORT, the term "node price" is used to measure the communication cost from a node to the sink as the path loss rate. Congestion ends in node price increase. The sink reports the fidelity required by the sink based on the node price. In this protocol, congestion detection is accomplished based on link loss rate and node price. Moreover, implicit congestion notification is used and traffic and resource control are utilized for congestion control. PORT makes energy consumption minimized in two ways where the first one feeds back the optimal reporting rates, however, the second one is an optimal routing technique which is based on the downstream communication condition feedback. In PORT, adaptation to communication conditions and maintaining the required reliability level is guaranteed. Simulation results confirm the superior performance of PORT in an application case study.

D. Delay Sensitive Transport Protocol (DST)

Delay Sensitive Transport protocol (DST) [15] is specifically suggested in case the sink late event notification renders application failure. DST mitigates congestion and guarantees reliability. It utilizes E-2-E mechanism for loss recovery purpose; however, loss detection and notification are not accomplished in DST. In this protocol, congestion detection is accomplished based on buffer occupancy and node delay.

Moreover, congestion is implicitly notified and rate adjustment is used to control congestion. The average delay varies according to the channel load and the used rate. In case the delay or buffer values in the congested nodes are more than a predefined value, the sink will be notified by a bit which is located in the packet header. By utilizing the current network condition and the reliability indicator, the sink adjusts the reporting frequency of sensors. Collision-based congestion is not avoided in DST; however, the source rate is decreased.

Destination-based Reliable Data Transport Protocols

Some well-known destination-based reliable data transport protocols are summarized as follows [55]:

A. GARUDA

GARUDA [55] is a H-by-H reliable data transport protocol which provides point-to-multipoint data transport from sink to sensors. Also, it focuses on energy conservation. In GARUDA, the reliable short message delivery is obtained using a pulsing-based solution. In this protocol, a NACK-based recovery process is established which can effectively minimize the retransmission process overhead. Finally, different reliability notions which are needed in wireless sensor networks are included in this protocol.

Loss Detection and Notification-based Reliable Data Transport Protocols

In this subsection, some well-known loss detection and notification-based reliable data transport protocols are categorized as ACK-based, NACK-based, ACK and NACK-based and Sack-based reliable data transport protocols which are as follows:

ACK-based Reliable Data Transport Protocols

Some well-known ACK-based reliable data transport protocols are summarized as follows [13], [18], [21], [26], [27], [29], [47], [49], [51], [53]:

A. Reliable Bursty Convergecast (RBC)

In Reliable Bursty Convergecast (RBC) [18], the challenges regarding bursty convergecast in multi-hop WSNs are addressed. In RBC, congestion detection is accomplished based on buffer occupancy and implicit congestion notification is used. Also, reliability is gained and a H-by-H mechanism is utilized for the loss recovery purpose. In RBC, channel utilization is enhanced by a window-less block ACK technique. Also, the received packet acknowledgment is replicated by the block acknowledgment which reduces the ack-loss probability. Moreover, an adaptive retransmission timer is utilized in RBC to deal with the continuously changing ack-delay which renders adaptation to the varying network states. Furthermore, resetting the retransmission timer and protecting the channel utilization render retransmission delay reduction and lost packet retransmission expedition.

B. A Redundancy-based Mechanism for Reliable and Fast Data Collection in WSNs

In this protocol, an adaptive scheme is used which provides low overhead, low delay and high reliability

[49]. It can adaptively change the redundancy level based on the application requirements and link loss rate. It is a network coding-based scheme which is utilized for message overhead reduction. It can be easily implemented, and is applicable for any kind of sensor networks. The protocol renders satisfactory performance in a real testbed.

C. TCP Support for Sensor Nodes (TSS)

TSS [21] ends in TCP energy-efficient operation in WSNs. In this protocol, TCP segments are cashed, and in case of error occurrence, local retransmissions are performed. In this protocol, congestion detection is accomplished based on buffer occupancy and packet rate. Also, implicit congestion notification is used and the rate adjustment technique is utilized for congestion control. The results show that TSS renders superior performance in comparison with TCP in terms of both throughput and the number of TCP segments which are transmitted. The protocol utilizes E-2-E mechanism for loss recovery purpose, and iACK mechanisms are used for loss detection and notification.

D. Tiny TCP/IP

Tiny TCP/IP [53] enhances TCP/IP protocol for WSNs and supports E-2-E and H-by-H reliability. TCP/IP protocol is not suggested for WSNs because of energy efficiency and throughput constraints. In this protocol, congestion detection is accomplished based on packet rate. Also, implicit congestion notification is used and rate adjustment is utilized for congestion control. The protocol utilizes both E-2-E and H-by-H mechanism for the loss recovery purpose, and iACK and eACK mechanisms are used for loss detection and notification. The drawbacks concerning Tiny TCP/IP are that it is not suitable for mobile WSN applications and congestion control cannot be explicitly accomplished.

NACK-based Reliable Data Transport Protocols

Some well-known NACK-based reliable data transport protocols are summarized as follows [19], [24], [28], [45], [46], [48], [50], [52], [54], [55]:

A. Group-based Reliable Data Transport (GRDT)

GRDT [45] is applicable in wireless body area sensor networks for periodical data acquisition. In GRDT, both TDMA and FDMA schemes are used where the former guarantees reliable data transmission and ends in delay reduction in network, however, the latter renders throughput enhancement. Moreover, the packet reception rate is significantly improved and the transmission delay is reduced in GRDT which is due to the fact that a block feedback message technique is used for H-by-H loss recovery scheme. In GRDT, congestion avoidance is achieved. Also, the mobility and scalability issues are supported in this protocol.

The results confirm high reliability and throughput in GRDT.

B. End-to-End Reliable and Congestion Aware Transport Layer Protocol (ERCTP)

ERCTP [28] is an upstream reliable data transport protocol which mitigates congestion and guarantees reliability. In this protocol, congestion detection is accomplished based on buffer occupancy. Moreover, implicit congestion notification is used and rate adjustment technique is utilized for congestion control. Also, reliability is gained using distributed memory concept. The protocol utilizes E-2-E mechanism for loss recovery purpose. Moreover, NACK mechanism is used for loss detection and notification. ERCTP is both energy-efficient and fair.

C. Wisden

In Wisden [48], the issue of structural data acquisition is studied in WSNs. It includes two mechanisms, namely, reliable data transport and data time-stamping where the former uses a hybrid E-2-E and H-by-H recovery and the latter is independent of global clock synchronization. In this protocol, a vibration card is specifically designed for structural applications. Also, the bandwidth limitations resulted from low-power wireless radios are overcome by utilizing the wavelet-based compression schemes where the feasibility is evaluated to improve latency and reduce data rate requirements. Wisden is implemented on the Mica-2 motes and it is deployed on a large network structure. In Wisden, topology management techniques are utilized and packet losses are recovered. Finally, a data synchronization technique is implemented in Wisden which ends in little overhead.

D. Ad-hoc Transport Protocol (ATP)

ATP [52] improves the performance of TCP in wireless networks. In ATP, the intermediate nodes calculate the transmission delay. Afterwards, the required E-2-E rate is sent by the receiver and the sender adjusts the rate based on that. In ATP, a selective ACK is utilized to obtain reliability. In this protocol, congestion is controlled by rate adjustment. The drawbacks of ATP are that it is not energy efficient and it uses E-2-E control pattern.

ACK and NACK-based Reliable Data Transport Protocols

Some well-known ACK and NACK-based reliable data transport protocols are summarized as follows [12], [14], [20], [43]:

A. Rate-Controlled Reliable Transport (RCRT)

RCRT [14] is a centralized sink-initiated transport protocol in WSN applications. In this protocol, initial Round-trip time (RTT) estimation and the desired source rate are used to establish an E-2-E connection with sink. In RCRT, congestion detection is accomplished based on loss repair time and implicit congestion notification is used. Also, the rate adjustment technique is utilized for congestion control. In this protocol, there exists an out of order received packet list which shows the loss elapsed time.

The NACK loss recovery is utilized; however, it tolerates moderate E-2-E losses. The aforementioned E-2-E protocol has slow reaction which ends in high energy consumption.

B. STCP

STCP [12] is a reliable data transport layer protocol which is generic and scalable and the majority of functionalities is implemented in the sink. It also mitigates congestion. In this protocol, congestion detection is accomplished based on buffer occupancy, implicit congestion notification is used and rate adjustment technique is utilized for congestion control. In STCP, the sink is informed by the sensor nodes through a “Session Initiation Packet” before transmitting packets.

In the aforementioned packet, the sink is informed about the source flow number, the transmission rate, the data type, and the reliability required. The sink sends an ACK to the source node in case it receives the abovementioned packet. Thereafter, the source node starts to send packets.

The packet header in STCP consists of sequence number, congestion notification bit, flow id, and a clock field. The next packet arrival time can be expected since the source transmission rate is obvious for the sink. The sink sets a timer and sends a NACK in case no packet is received in the expected time.

Sack-based Reliable Data Transport Protocols

Some well-known Sack-based reliable data transport protocols are summarized as follows [22], [51]:

A. Real-time and Reliable Transport $(RT)^2$

$(RT)^2$ [22] is a reliable energy-efficient transport protocol for WSNs. In $(RT)^2$, congestion detection is accomplished based on buffer occupancy and delay, implicit congestion notification is used and the rate adjustment technique is utilized for congestion control. In this protocol, both sensor-actor and actor-actor communication exist where in the former the communication process is accomplished between sensors to actors, however, in the latter, it is established between actors.

Also, the reliability characteristics are sensor-actor and actor-actor transport reliability.

Loss Recovery-based Reliable Data Transport Protocols

In this subsection, some well-known loss recovery-based reliable data transport protocols are categorized as E-2-E and H-by-H reliable data transport protocols which are as follows:

E-2-E Reliable Data Transport Protocols

Some well-known E-2-E reliable data transport protocols are summarized as follows [12], [14], [15], [17], [19]-[21], [24]-[26], [28], [29], [43], [44], [47], [49], [50], [52], [53]:

A. Event to Sink Reliable Transport (ESRT)

In ESRT [17], the reliability issue is considered at the application level where the stochastic reliable packet delivery is guaranteed.

ESRT is an E-2-E protocol which regulates the frequency of sensor report to provide a desired level of reliability. In ESRT, reliability is provided for applications rather than packets. In this protocol, the current network state determines the protocol operation according to the reliability obtained and the congestion level.

In ESRT, the factual reliability is periodically computed based on the received packets in the specified time interval. Afterwards, the required sensor report frequency is deduced and the sensors are informed. In this protocol, the current state is identified and the network is aimed to be in the optimal operating region. In ESRT, the source node reporting frequency is adjusted so that the reliability level reaches the desired value. In ESRT, in case the reliability is lower than the desired value, the source node reporting frequency is adjusted so that the reliability level reaches the desired value. On the other hand, in case the reliability is higher than the desired value, the source node reporting frequency is reduced so that the energy is conserved while at the same time reliability is maintained. In this protocol, congestion detection is accomplished based on buffer occupancy, implicit congestion notification is used and rate adjustment technique is utilized for congestion control.

The benefits obtained from ESRT are that it is an energy-conserving protocol, and that it has a self-configuring nature which guarantees its robust performance in dynamic and random topologies in wireless sensor networks.

However, the drawbacks in this protocol are that it does not handle different event types so different levels of reliability are needed and, in this protocol, all nodes are equally treated which ends in throughput degradation.

B. Reliable Transport Protocol with a Cache-Aware Congestion Control (RT-CaCC)

The reliability issue in data transport in WSNs is of paramount importance in case of packet loss. Reliability can be enhanced using congestion control and intermediate caching. RT-CaCC [50] is a reliable data transport protocol with a cache-aware congestion control in WSNs. In this protocol, packet loss reduction and cache utilization enhancement are gained using cache insertion, elimination, and size allocation. In this protocol, an analytical model is derived to evaluate the performance in case of packet loss. The results confirm the effectiveness of RT-CaCC in terms of cache utilization, fairness, and E-2-E delay.

H-by-H Reliable Data Transport Protocols

Some well-known H-by-H reliable data transport protocols are summarized as follows [13], [18], [22]-[24], [27], [40]-[42], [45], [46], [48], [51], [53], [54]:

A. Directed Diffusion (DD)

DD [40] is a data centric protocol where all nodes are application-aware which enables DD to save energy by choosing good paths. The protocol has some elements, namely, interests, gradients, data messages, and reinforcements. The interest message is a sink query to network which includes the sensing task description and also it shows what the application wants. Data in WSNs is collected and addressed, and the sensing task diffusion is accomplished in the network as an interest for the named data. The aforementioned dissemination introduces gradients which are used to "draw" events. The gradient is considered as a direction state in each node which receives an interest. The direction is set toward the neighbor node where the interest is received. Events start to flow towards the sinks of interests in multiple gradient paths. The sink introduces the good paths. Also, unreliable paths are pruned off. The results confirm the effectiveness of DD in terms of energy saving.

B. Extended Datagram Congestion Control Protocol (EDCCP)

EDCCP [41] is a data transport protocol which is used to provide congestion control and the corresponding negotiations in multimedia applications. In EDCCP in order to enhance reliability, the received packets are buffered at the receivers, the corrupted packets are retransmitted by the senders, the duplicated packets are detected and deleted at the receivers, and finally, the in-order delivery of the received packets is accomplished. Also, there exist four states in the sender, namely, normal, congestion, failure, and the transmission error. EDCCP provides reliability and good throughput.

C. Reliable Data Transport Protocol (RDTP)

The reliable transport of data from sensor nodes to the sink node is of paramount importance. In order to design reliable transport protocols, the processing power and energy shall be considered. In [42], RDTP is presented for wireless sensor networks. In RDTP, a modulus set is used in the redundant residue number system to add redundancy to the transmitted data. In RDTP, error control is accomplished in a H-by-H manner. The results confirm that RDTP ends in significant decrease in E-2-E delay which ends in energy efficiency. It also shows packet delivery ratio increase comparing with similar methods.

D. XLP

XLP [13] performs congestion control, routing, and MAC in WSNs in a cross-layer and H-by-H fashion. In XLP, the generated packet rate at node is controlled. Since congestion occurs in a certain region, the corresponding nodes may reduce their transmission rates. In this protocol, the handshake message exchange ends in overhead in wireless sensor network.

In XLP, congestion detection is accomplished based on buffer occupancy, implicit congestion notification is used and the traffic control technique is utilized for congestion control.

E. Tunable Reliability with Congestion Control for Information Transport (TRCCIT)

TRCCIT [27] is a H-by-H reliable transport protocol for WSNs which controls congestion by monitoring the information and adapting the paths. Path adaptation is accomplished such that the information is transported to multiple paths rather than a single one. In this protocol, congestion detection is accomplished based on packet rate and implicit congestion notification is used. TRCCIT performance is studied in terms of reliability of transport information, timeliness and efficiency.

F. Distributed TCP Caching (DTC)

In DTC [51], the TCP drawbacks in terms of both energy efficiency and throughput are rectified in WSNs. In this protocol, local retransmissions and caching the segments are utilized to avoid E-2-E retransmissions. Also, transmitting the TCP segments is reduced, E-2-E retransmissions is decreased and energy is consumed.

Results and Discussion

In this section, first, the above-mentioned reliable data transport protocols are compared with each other. Tables 1, 2, 3 and 4 summarize the traffic direction-based, parameter-based, loss detection and notification-based and loss recovery-based reliable data transport protocols, respectively. In the aforementioned Tables, congestion detection, notification and mitigation of several reliable transport protocols are outlined. Also, the reliability direction and level, and the loss detection, notification and recovery in the aforementioned protocols are presented. Also, the evaluation type and the comparison with protocols are outlined and the fairness and the energy conservation are presented. Afterwards, in Table 5, the aforementioned protocols are compared using different parameter evaluation metrics.

Table 1: Comparison of Traffic direction-based reliable data transport protocols

Protocol	Congestion detection	Congestion notification	Congestion mitigation	Reliability direction	Reliability level	Loss Detection and notification	Loss recovery	Compared with	Energy conservation	Fairness	Evaluation type
ERTP [47]	-	-	-	Upstream	Packet	eACK, iACK	E-to-E	Surge Reliable	Yes	No	Simulation, experimentation TinyOS operating system
DTSN [43]	-	-	-	Upstream	Packet	NACK, eACK	E-to-E	-	Yes	No	Simulation OMNET++
PSFQ [54]	-	-	-	Downstream	Packet	NACK	H-by-H	-	Yes	No	Simulation NS2, experimentation TinyOS operating system
Flush [19]	Queue length, Link interference	Implicit	Rate Adjustment	Upstream	Packet	NACK	E-to-E	-	No	No	Experimentation
ART [20]	ACK received to essential nodes	Implicit	Non-essential node traffic reduction	Both	Event	eACK, NACK	E-to-E	-	Yes	No	Simulation NS2

Table 2: Comparison of Parameter-based reliable data transport protocols

Protocol	Congestion detection	Congestion notification	Congestion mitigation	Reliability direction	Reliability level	Loss Detection and notification	Loss recovery	Compared with	Energy conservation	Fairness	Evaluation type
DST [15]	Node Delay, Queue Length	Implicit	Rate Adjustment	Upstream	Event	-	E-to-E	ESRT	Yes	No	Simulation NS2
PORT [16]	Node price and the link loss rate	Implicit	H-by-H Resource control and E2E Traffic Control	Upstream	Event	-	No	Directed Diffusion, ESRT	Yes	No	Simulation NS2
RMST [46]	-	-	-	Upstream	Packet	NACK,MAC	H-by-H	-	No	No	Simulation
CTCP [29]	Queue length, the transmission error loss	Explicit	Rate Adjustment	Upstream	Packet	eACK, double eACK	E-to-E	-	Yes	No	Experimentation TinyOS operating system
RTMC [23]	Memory overflow	Implicit	Rate Adjustment	Upstream	Packet	-	H-by-H	SEA	Yes	No	Experimentation
CRRT [24]	Queue length, packet rate	Implicit	Rate Adjustment	Upstream	Packet	NACK, MAC	E-to-E, H-by-H	RCRT	Yes	Yes	Simulation NS2
E^2SRT [25]	Queue length	Implicit	Rate Adjustment	Upstream	Event	-	Event-to-sink	ESRT	Yes	No	Simulation NS2
LTRES [26]	Link loss rate	Implicit	Rate Adjustment	Upstream	Event	SIP-ACK, GNP-ACK	Event-to-sink	LSR	Yes	Yes	Experimentation

Table 3: Comparison of Loss detection and notification-based reliable data transport protocols

Protocol	Congestion detection	Congestion notification	Congestion mitigation	Reliability direction	Reliability level	Loss Detection and notification	Loss recovery	Compared with	Energy conservation	Fairness	Evaluation type
TSS [21]	Packet rate, queue occupancy	Implicit	Rate Adjustment	Upstream	Packet	iACK	E-to-E	-	Yes	No	Omnet++ simulator
(RT)^2 [22]	Queue length, node delay	Implicit	Rate Adjustment	Upstream	Packet	SACK	H-by-H	ESRT, TCP-New Reno, TCP-ELFN, ATP	Yes	No	Simulation NS2
Tiny TCP/IP [53]	Packet rate	Implicit	Rate Adjustment	Upstream	Packet	eACK, iACK	E-to-E, H-by-H	-	Yes	No	Experiment ation
ATP [52]	Queue length	Explicit	Rate Adjustment	Upstream	Packet	NACK	E-to-E	TCP, TCP-ELFN ,ATCP	No	Yes	Simulation NS2
ERCTP [28]	Buffer occupancy	Implicit	Rate Adjustment	Upstream	Packet	NACK	E-to-E	TCP-WW+, TCP-WW, TCPNew Reno, TCPReno	Yes	Yes	Simulation
RBC [18]	Remaining Queue Length	Implicit	Rate Adjustment	Upstream	Packet	iACK	H-by-H	SEA, SWIA	No	No	Experiment ation
RCRT [14]	Time for Loss repair	Implicit	Rate Adjustment	Upstream	Packet	NACK, cumm. ACK	E-to-E	IFRC	No	Yes	Experiment ation
STCP [12]	Queue size	Implicit	Rate Adjustment traffic redirection	Upstream	Packet	NACK, eACK	E-to-E	-	Yes	No	Simulation NS2

Table 4: Comparison of Loss recovery-based reliable data transport protocols

Protocol	Congestion detection	Congestion notification	Congestion mitigation	Reliability direction	Reliability level	Loss Detection and notification	Loss recovery	Compared with	Energy conservation	Fairness	Evaluation type
XLP [13]	Queue size	Implicit	Traffic control	Upstream	Event	ACK	H-by-H	ALBA-R, DD-RMST, PRR-SMAC, Flooding, GEO	Yes	No	Simulation NS2
ESRT [17]	Queue length	Implicit	Rate Adjustment	Upstream	Event	-	E-to-E	-	Yes	No	Simulation
TRCCIT [27]	Packet rate	Implicit	Rate Adjustment	Upstream	Packet	eACK, iACK	H-by-H	RBC, MMP	No	No	simulation

Different metrics are used to evaluate the performance of the reliable data transport protocols [68]. The features and evaluation metrics are the source rate, throughput, goodput, network efficiency or life time, energy efficiency, packet loss ratio, fairness, memory requirements, end-to-end delay, instantaneous queue size, control packet overhead, fidelity index and penalty where the schemes are compared regarding the aforementioned features in Table 5.

Table 5: Comparison of reliable data transport protocols in WSNs based on different performance metrics

Protocol	Performance metrics	Protocol	Performance metrics
STCP [12]	Packet Latency, Energy Spent	Flush [19]	Throughput, number of each node transmissions, packet rate
XLP [13]	Goodput, latency, energy consumption	CTCP [29]	Energy consumption, the number of received packets
RCRT [14]	Goodput, Rate, Packet Reception	ART [20]	Residual energy, Network lifetime, E2E delay, Packet loss ratio
DST [15]	Convergence Time, Energy Consumption	TSS [21]	Throughput, Memory Consumption, Overhearing Time, Local RTT Measurements
PORT [16]	Energy Consumption	$(RT)^2$[22]	Communication latency, energy consumption, Throughput, Delay
ERTP [47]	Energy consumption, Average packet delay	RTMC [23]	Transport time, memory cost
ESRT [17]	Normalized Reliability, Average Power Consumption	CRRT [24]	Goodput, source rate, energy efficiency
DTSN [43]	Throughput, energy-efficiency	E^2SRT [25]	Energy consumption, throughput, loss rate, latency
RBC [18]	Packet Delivery Delay, Loss Ratio	Tiny TCP/IP [53]	Packet loss, loss rate
RMST [46]	Error Rate, Number of Retries	LTRES [26]	Packet loss rate, overall bandwidth utilization, fairness
PSFQ [54]	End-to-end delay, packet loss	ATP [52]	Throughput, fairness
TRCCIT [27]	Information transport reliability and timeliness, message complexity	ERCTP [28]	Throughput, average E-2-E data packet latency, average data packet drop, energy consumption

Conclusion

In general, congestion algorithms in wireless sensor networks are classified as congestion mitigation, congestion avoidance, and reliable data transmission. Congestion mitigation schemes are classified according to the way congestion is detected, notified to nodes, and faced. Congestion can be detected using different metrics.

Congestion notification is accomplished either explicitly or implicitly. Congestion control algorithms are listed under 13 categories, i.e. traffic control, resource control, traffic and resource control, fairness-based, priority-aware, E-2-E or H-by-H, energy efficient, reliability-based, queue-assisted, centralized or distributed, generic or cross layer, content-aware and soft computing-based congestion control schemes. Congestion avoidance can be accomplished using rate adjustment, traffic redirection and polite gossip policy.

In reliable data transport protocols, congestion is controlled and the lost information is recovered. They are mostly used in case all information is of paramount importance for the application. Reliable data transport protocols are classified as the traffic direction, the parameter the reliability focuses on and loss detection, notification, and recovery. Traffic direction-based reliable data transport protocols can be upstream, downstream or bidirectional. Parameter-based reliable data transport protocols can be packet-based, event-based or destination-based. Loss detection and notification-based reliable data transport protocols can be ACK-based, NACK-based, ACK and NACK-based or Sack-based.

Loss recovery-based reliable data transport protocols can be E-2-E or H-by-H. In this paper, a comprehensive review of reliable data transport protocols in wireless sensor networks is presented. Also, different performance metrics as the source rate, throughput, goodput, network efficiency or life time, energy efficiency, packet loss ratio, fairness, memory requirements, end-to-end delay, instantaneous queue size, control packet overhead, fidelity index and penalty are used to compare these schemes. These protocols tackle the transport problems in wireless sensor networks from several aspects.

Future Directions

Future directions for data transport protocols in wireless sensor networks should consider the following items:

- A data transport protocol which provides sensor-to-sink and sink-to-sensor data transmission is required, however, the existing protocols emphasize on only one direction and not both directions. Furthermore, conflict or confusion between these protocol types may exist in case they are not well organized in a unified framework.
- The interaction between congestion control and the reliability issue shall be studied. A protocol which provides congestion control and reliability is demanded.

- Reliable transport protocols shall be cross layer to be able to improve the communication system performance.
- The possibility of using mobile agent techniques for performance enhancement shall be addressed.
- Energy efficiency shall be considered in the design of transport protocols for wireless sensor networks.
- QoS provisioning in wireless sensor networks shall be studied in the design of reliable transport protocols.
- In addition to transport reliability, other reliability aspects as the node reliability/life time and node placement to reliably cover event areas shall be taken into consideration.
- The security issue shall be considered in the design of transport protocols for wireless sensor networks.
- Experimental methods shall be applied to transport protocols to demonstrate their effectiveness in real life scenarios.
- Data transport protocols shall be easily implementable due to the existing energy and memory constraints of sensors in wireless sensor networks.
- The issue of being real time shall be considered in the design of transport protocols in wireless sensor networks.

Author Contributions

Shoorangiz Shams Shamsabad Farahani carried out writing the whole paper without participation of anybody, all parts of the manuscript are accomplished by herself as the single author and the corresponding author of the current study.

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Conflict of Interest

The author, Shoorangiz Shams Shamsabad Farahani declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by me.

Abbreviations

WSNs	Wireless Sensor Networks
QoS	Quality of service
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
E-2-E	End-to-end
AIMD	Additive-Increase Multiplicative-Decrease
H-by-H	Hop-by-hop
AIAD	Additive increase additive decrease
ACK	Positive acknowledgements
NACK	Negative acknowledgements
SACK	Selective ACK
ERTP	Energy-efficient and Reliable Transport Protocol
DTSN	Distributed transport for sensor networks
PSFQ	Pump Slowly, Fetch Quickly
ART	Asymmetric and Reliable Transport
RTMC	Reliable Transport with Memory Consideration
CRRT	Congestion-Aware and Rate-Controlled Reliable Transport
CTCP	Collaborative Transport Control Protocol
RMST	Reliable Data Transport in Sensor Networks
RDTS	Reliable erasure-coding based data transfer scheme
E^2SRT	Enhanced Event-to-Sink Reliable Transport
LTRES	Loss-Tolerant Reliable Event Sensing
PORT	Price Oriented Reliable Transport protocol
DST	Delay Sensitive Transport protocol
RBC	Reliable Bursty Convergecast
TSS	TCP Support for Sensor Nodes
GRDT	Group-based Reliable Data Transport
ERCTP	End-to-End Reliable and Congestion Aware Transport Layer Protocol
ATP	Ad-hoc Transport Protocol
RCRT	RATE-Controlled Reliable Transport
$(RT)^2$	Real-time and Reliable Transport
ESRT	Event to Sink Reliable Transport
RT-CaCC	Reliable transport protocol with a cache-aware congestion control
DD	Directed Diffusion
EDCCP	Extended Datagram Congestion Control Protocol
RDTP	Reliable data transport protocol
TRCCIT	Tunable Reliability with Congestion Control for Information Transport
DTC	Distributed TCP Caching

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