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Review

Congestion control mechanisms in wireless sensor networks: A survey

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ABSTRACT

Congestion control is deemed to be one of the most significant challenges in Wireless Sensor Networks (WSNs) which is attributed to resource constraint specification and the number of deployed nodes. In WSNs, congestion is caused by the following factors: packet collision, node buffer overflow, transmission channel contention, transmission rate, many-to-one data transmission scheme and dynamic time variation transmission channel. Indeed, congestion has a significant impact on Quality of Services (QoS) parameters such as packet delivery ratio (PDR), end-to-end delay and energy consumption in wireless nodes. This paper presents a comprehensive survey of major congestion control mechanisms used in WSNs and classifies the available methods into four categories i.e. traffic control protocols, resource control protocols, queue assisted protocols and priority-aware protocols. This review paper compares the important techniques with each other in terms of congestion detection, congestion notification and congestion mitigation as well as directions for future researches and works.

Contents

1. Introduction

In recent years, advances in micro-electromechanical systems (MEMS), wireless networks and very large-scale integrated circuit (VLSI) design have enhanced the importance of WSNs as a remarkable technology for mission-critical tasks (Akyildiz et al., 2002; Yick et al., 2008). These networks play a vital role in many fields and applications such as habitat and environment monitoring (Biagioni and Bridges, 2002; Cerpa et al., 2001), target tracking (Brooks et al., 2003; Kung and Vlah, 2003), structural health monitoring (Schwiebert et al., 2001) and critical infrastructure

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protection (Chen et al., 2011). In WSNs, sensor nodes have limited resources with regard to computation, storage, communication bandwidth and, most importantly of all, energy supply. These specifications and inherent constrains have affected QoS parameters such as packet delivery ratio, end-to-end delay, bandwidth utilization and average node energy consumption in WSNs (Akyildiz et al., 2002; Yick et al., 2008). Hence, researchers should consider these resource specifications and constraints in different applications so as to improve the above-mentioned QoS parameters.

Due to the event-driven nature of WSNs, resource constraints, many-to-one communications, number of deployed sensors and the high traffic of sensor nodes lead to the creation of congestion in these networks. In WSNs, network congestion occurs when the offered traffic load exceeds the available capacity at any point in the network (Flora, 2011). Indeed, it can be mentioned that congestion is one of the highly critical challenges in WSNs and it has a profound impact on QoS parameters and the energy efficiency of sensor nodes. Moreover, congestion increases packet loss and degrades the throughput or wireless channels. Thus, in order to handle such challenges and problems in WSNs, researchers should consider and control the factor of congestion (Fig. 1).

As Fig. 2 illustrates, congestion in WSNs is created at two levels: *node-level congestion* (or buffer overflow) and *link-level congestion*. In *node-level congestion*, when packet arrival rate is higher than packet service rate, congestion is caused. This type of congestion occurs mostly in those sensor nodes which are closer to the sink. Node-level congestion increases packet loss and power waste in WSNs. Consequently, this type of congestion has a direct impact on network availability and network lifetime. Factors such as competition, collision and bit error result in *link-level congestion*. Thus, in this kind of congestion, packet delivery rate in sink node is reduced. Therefore, for enhancing throughput and packet delivery rate at sink node, collision should be prevented by using an appropriate medium access control based congestion control algorithms.

Firstly, congestion should be detected in sensor nodes known as congestion detection phase. Secondly, as congestion occurs, upstream sensor nodes should be notified of congestion referred to as notification phase. Finally, congestion should be mitigated and appropriate data rate should be selected, known as rate adjustment or congestion mitigation phase. Thus, the process of congestion control includes three phases: congestion detection, congestion notification and congestion mitigation. Several congestion detection techniques have been proposed for WSNs i.e. occupied queue length, packet service time, packet interval and packet service time, packet drop at the sink node, queue length

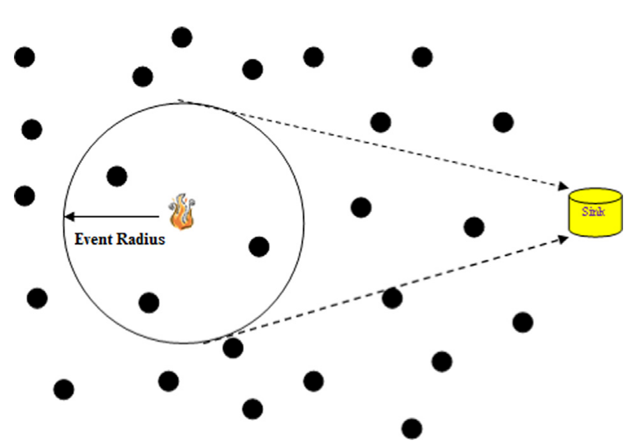

Fig. 1. Many-to-one data transmission scheme in WSNs.

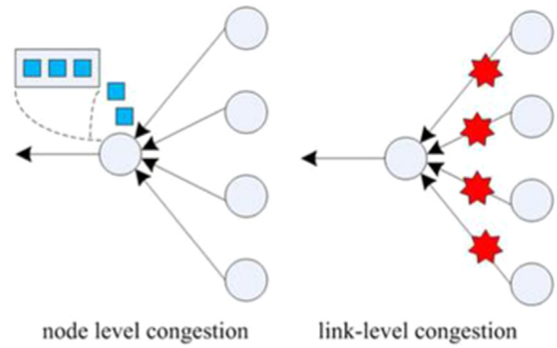

Fig. 2. Common congestion positions in WSNs.

and channel state and dual buffer thresholds and weighted buffer difference.

This review paper is intended to highlight a critical issue and problem in WSNs; in other words, congestion control algorithms for WSNs have been examined and outlined and their pros and cons of have been briefly discussed. In fact, numerous congestion control techniques have been proposed for WSNs. However, the investigation of the proposed techniques indicates that congestion has an undeniably significant impact on the performance and efficiency of WSNs. Consequently, it should be noted that the optimization and improvement of performance is a challenging task for WSNs. This issue has triggered a variety of research and study on the design and implementation of appropriate and efficient techniques on congestion control. Indeed, handling and controlling congestion in WSNs is considered to be a remarkable research gap which has attracted researchers' attention.

The major contributions of this review paper are as follows: this review paper overviews the related literature and pinpoints the most important and updated congestion control mechanisms which have been proposed for WSNs. This review paper characterizes and highlights the different approaches to designing and improving congestion control by focusing on their strategies, merits and demerits. Furthermore, this paper collects, classifies, analyzes, and compares the major congestion control protocols for WSNs.

This review paper has focused on the following issues: congestion detection, congestion notification, congestion control, control pattern and generic or cross-layer congestion control mechanisms. Ultimately, this paper discusses the major challenges in congestion control protocols for WSNs and recommends directions for further research on the design and implementation of appropriate new congestion control techniques.

The rest of the paper is organized as follows: Section 2 reviews the related works on congestion control. Section 3 provides an overview on related issues in WSNs and presents a brief review of each protocol and classifies the most popular congestion control algorithms based on the strategies used for congestion detection, notification and mitigation. Section 4 compares different congestion control protocols in WSNs with respect to their strategies and common evaluation parameters. Section 5 presents a discussion for this review paper. Section 6 concludes this paper and recommends directions for further research.

2. Related works

Despite the bulk of protocols proposed for congestion control, it remains an unresolved and thorny issue. Some significant survey and review studies related to the above-mentioned research problem are mentioned below.

A few congestion control schemes have been proposed for WSNs (Zhao et al., 2010). They used media access control layer, MAC and network layer (cross-layer) schemes to categorize the existing congestion control techniques. Having reviewed numerous congestion control techniques, they concluded that cross layer schemes have better performance and efficiency than single layer mechanisms in large scale networks. Hence, it can be maintained that the performance of MAC-layer-based congestion control schemes such as carrier scene with multiple access control (CSMA) should be improved either by changing its operation or by combining it with time division multiple access (TDMA) mechanism. Also, they concluded that there should be some balance between stability and fairness in designing and implementing congestion control algorithms. However, it should be noted that they failed to compare the reviewed congestion control techniques with one another.

Flora (2011) reviewed congestion control techniques in WSNs. He reviewed and compared the existing limited number of research studies on congestion control in WSNs without any classifications. Also, he reviewed different performance metrics used for measuring congestion in WSNs. Nevertheless, he failed to include the impacts and findings of the conducted studies and did not discuss the theoretical and practical implications of the available studies. Dashkova and Gurtov (2012) presented a review of congestion control algorithms in constrained environments. They contended that congestion can result in catastrophic events and phenomena; they formulated an effective scheme in which they underlined all the important assumptions. Having reviewed several seminal papers on congestion control, they argued that the integration of active queue management scheme (AQM)-beacon order-based random early detection (BoB-RED) (Lin et al., 2011) and explicit congestion notification (ECN) bits usage is deemed to be an effective scheme for congestion control in WSNs. Junghare and Shimpi (2012) carried out a survey study on congestion control protocols. They reviewed the studies on congestion control schemes in WSNs and examined their advantages and disadvantages. However, they failed to compare the reviewed congestion control techniques with one another. Moreover, it should be noted that this review paper did not present a comprehensive and profound discussion and classification of the related literature and did not highlight any important directions for further research. Rezaei and Rafsanjani (2012) reviewed the few available research studies on congestion control in WSNs and compared them with one another. Nevertheless, they did not use any classifications, discussions and did not recommend directions for further research. Gowthaman and Chakravarthi (2013) conducted a survey on the under-researched issues of congestion detection and control protocols in WSNs and compared them with each other. They also suggested some research agenda and open questions for future works. As a case in point, they mentioned that energy efficiency over transport protocols should be investigated and examined in future works. Another highlighted issue in that review paper was that a unified protocol which can handle both reliability and congestion control is needed. Sergiou et al. (2014) outlined and classified a large set of congestion control schemes for WSNs and discussed the characteristics, advantages and disadvantages of each approach. Kafi et al. (2014) reviewed and classified many congestion control approaches for WSNs. Based on control policy, they divided congestion control mechanisms into resource control and traffic control. These researchers also classified traffic control schemes into reactive and preventive types. Based on this categorization, resource controls can be classified according to the type of resources to be tuned.

The above-mentioned discussion reveals that although some attempts have been made to survey and review important issues on congestion control mechanisms, there are overwhelmingly few comprehensive and detailed reviews of studies and issues on presented congestion control techniques for WSNs. In other words, review papers that can identify research gaps, cutting-edge issues and introduce novel ideas on congestion control are rare. The present review paper is aimed at filling the gap and demonstrating the state of art on congestion control. Indeed, this review paper surveys and reviews the proposed techniques and contributions and presents classifications, discussions, comparisons and recommendations about different aspects and features of congestion control.

3. An overview of issues on congestion control in WSNs

Recently, increasingly rapid advances in WSN and their applications have drawn researchers' attention towards different issues in these networks. Indeed, WSNs are applied in a wide range of fields from academic to healthcare and home to industrial fields. Special mission-critical applications result in huge data loads. Due to constraint resources in WSNs, huge data loads can easily lead to congestion. Thus, these challenges of WSNs need to be addressed by interested researchers in this field.

Since congestion causes considerable delays in these networks; data packets are likely to be lost and high amounts of energy is consumed in forwarding packet toward the sink node. Thus, congestion control is one of the most critical problems in designing and implementing WSNs. It should be noted that congestion in WSNs is much more complicated than congestion in other networks. In other words, in WSNs, different types of congestion may occur in different points and locations of a WSN.

Jaewon et al. (2007) categorized the reasons for congestion occurrence into two types: (a) simultaneous transmission and (b) buffer overflow. In event-based applications, simultaneous data reporting and transmission lead to packet loss which are attributed to interference. An efficient MAC layer and explicit local synchronization with neighbor nodes can reduce this type of packet loss. Since non-neighboring nodes can affect data transmission and they interfere with it, this type of packet loss cannot be eliminated thoroughly. Buffer overflow is regarded as the second reason and justification for packet loss in WSNs. That is, when a node in WSNs receives more packets than it can forward, the queue or buffer of node overflows. This overflow results in packet loss. In fact, buffer overflow occurs when a node receives such huge data that is beyond its transmission capacity.

3.1. Congestion detection

Congestion detection refers to the process of detecting and finding the presence and location of congestion in WSNs. In congestion control protocols, different parameters are used for detecting congestion: buffer occupancy (queue length), channel load, buffer occupancy and channel load (Wan et al., 2011; Yin et al., 2009; Lee and Chung, 2010; Paek and Govindan, 2010; Zawodniok and Jagannathan, 2007; Brahma et al., 2010). Some protocols use a combination of the above mentioned parameters for detecting congestion.

(a) **Buffer occupancy (queue length):** In WSNs, each sensor node has a buffer (queue) which is used for buffering the incoming packets. In this case, buffer occupancy is a good indication of congestion. For example, (Chen and Yang, 2006; Chen and Zhang, 2006; Teo et al., 2008) used a constant threshold for queue length; that is, when buffer occupancy level of nodes exceeds these constant thresholds and congestion is detected, alarm is raised.

(b) **Channel load:** Protocols using channel load for congestion indication only compute packet load in the wireless medium and take an appropriate decision when the time frame for the transmission of a data packet exceeds the predefined threshold.
(c) **Packet service time:** It refers to the time difference between packet arrival at the medium access control layer and its transmission time. This parameter is equal to one-hop node delay.
(d) **Combination of buffer occupancy and channel load:** The protocols using this parameter can detect congestion either in the buffer or in the wireless medium. When packet collision rate increases and when MAC is retransmitted unsuccessfully for several times, packets are removed. Thus, the resulted decrease in buffer occupancy attributed to such packet drops might be wrongly assumed as a congestion reduction; however, for obtaining precise congestion detection, a hybrid approach should be taken into consideration.

3.2. Congestion notification

When congestion is detected, upstream nodes should be informed so that they can adopt the right measure against the caused congestion. Congestion information can be propagated explicitly or implicitly. Some congestion control protocols notify the congestion by setting *congestion notification* (CN) bit in the packet header (Chakravarthi et al., 2010).

3.2.1. Explicit congestion notification

In this type of congestion notification technique, by transmitting additional control packets to upstream sensor nodes, congested nodes inform the upstream nodes of their congestion state. Since additional control packets are imposed to the already high loads in the congested area in this method, it is used by fewer congestion control mechanisms (Zhou et al., 2005; Jaewon et al., 2007; Tezcan and Wang, 2007; Faisal et al., 2009; Teo et al., 2008; Yin et al., 2009).

3.2.2. Implicit congestion notification

Unlike explicit method, this technique does not insert further load to the network and the congested nodes. In this type of congestion notification scheme, the congested nodes inform other sensor nodes by piggybacking the congestion information in a payload packet header. A number of congestion control protocols apply ACK signaling to indicate the congestion state. A large number of congestion control techniques use this technique for congestion notification (Akan and Akyildiz, 2005; Ee and Bajcsy, 2004; Tao and Yu, 2010; Wan et al., 2007; Wang et al., 2007).

In this paper, the researcher reviews both explicit and implicit congestion notification schemes and classifies them into different congestion notification techniques in term of their explicitness and implicitness as well as other criteria such as congestion detection and congestion mitigation.

3.3. Congestion control

Recently, a variety of different protocols have been proposed for controlling congestion in WSNs (Sankarasubramaniam et al., 2003; Wang et al., 2006; Antoniou et al., 2013; Brahma et al., 2012; Jaewon et al., 2007; Sergiou et al., 2013; Mahdizadeh Aghdam et al., 2014; Rezaee et al., 2014). These protocols are different in terms of congestion detection, congestion notification and rate adjustment techniques.

In this section of the paper, major congestion control mechanisms in WSNs are reviewed. Congestion control and rate adjustment techniques are classified into the following four categories:

(a) **Traffic control**: In this technique, congestion is mitigated by means of reducing the number of packets injected into WSNs. Traffic control techniques are categorized according to additive increase multiplicative decrease (Chiu and Jain, 1989) (AIMD) (Vuran and Akyildiz, 2010; Wan et al., 2011) or a rate-based method. AIMD-based traffic control scheme examines and checks the available network bandwidth via slow enhancement of congestion window. In congestion detection condition, the protocol decreases the congestion window significantly. AIMD-based scheme does not call for previous information about the available bandwidth of the network. By using mathematical equations, the rate-based scheme calculates the available bandwidth of the network explicitly (Akan and Akyildiz, 2005; Wang et al., 2007; Zawodniok and Jagannathan, 2007; Yaghmaee and Adjeroh, 2009; Yin et al., 2009). In the traffic control method, only the source node mitigates the congestion. Since in event-based applications, traffic reduction can have an impact on the valuable data packets carrying the information about the event, it can be argued that this method is not efficient for event-based application.
(b) **Resource control**: One of the disadvantages of traffic control scheme is valuable data rate reduction. In some applications, reducing the source data rate is desirable. For example, in event-based or critical-mission applications, all important data should be delivered to the sink. For eliminating the shortcomings of the traffic control scheme, an alternative technique, referred to as resource control was used in several congestion control protocols (Antoniou et al., 2013; Jaewon et al., 2007). In this case, congestion is handled by, for example, increasing network resources or using other idle or uncongested paths for the transmission of data towards the sink. In the resource control approach, when network is congested, data packets use alternative paths to reach the sink. This technique improves packet delivery rate better than the traffic control scheme.
Some applications use a combination of traffic control and resource control schemes for mitigating congestion; hence, they take advantages of both methods.
(c) **Priority-aware congestion control scheme**: Some protocols do not use the above-mentioned schemes; rather, they use prioritized MAC techniques to give the congested nodes a prioritized channel access. In other words, in this scheme, congestion is managed by considering different priorities in congestion situations.
(d) **Queue-assisted technique**: Congestion is tackled by the queue length of the nodes. The queue-assisted protocols mainly focus on the queue length of the nodes and use a simple rate adjustment technique such as Additive Increase Multipartite Decrease (AIMD) to keep the queue length of nodes as low as possible.

In brief, it should be pointed out that when a congestion control mechanism is selected, it should be able to answer the application requirements and it should consequences on network lifetime.

3.3.1. Traffic control mechanism

In this section, the specifications of traffic control mechanisms of congestion control in WSNs and their main properties are firstly described. Secondly, most popular traffic control mechanisms in

WSNs are extrapolated. Finally, the discussed protocols are compared and summarized.

In traffic control mechanisms, for reducing data rate on congested nodes, backpressure messages are used which are relayed backwards to the data sources until the data rate is controlled. In this model of congestion, a number of flows with low data rates may transmit data through a specific intermediate node which leads to congestion. A significant disadvantage of this method is that the reduction of data rate might negatively affect network mission (Sergiou et al., 2013).

Based on the above-mentioned shortcomings, it can be maintained that this type of congestion control mechanism is not efficient for event-based applications. As the data rate of source node decreases, the occurred event cannot be reported to sink. Inasmuch as all data packets carry valuable information about phenomena, rate reduction can have a negative impact on network mission. Since congestion control has a remarkable and undeniable role in optimizing QoS parameters in WSNs, many techniques and protocols have been proposed on the issue of congestion control.

3.3.1.1. Popular traffic control mechanisms. Extensive research work has been done in the area of congestion control algorithm for WSNs. In this section, some important and popular traffic control mechanisms in WSNs are presented and reviewed. Presented protocols are sorted based on the year of publication. The discussed congestion control schemes are compared based on their advantages and disadvantages.

3.3.1.1.1. ARC. Woo and Culler (2001) introduced the Adaptive Rate Control protocol which was aimed at monitoring the injection of packets into the traffic stream as well as route-through traffic. In ARC, each node estimates the number of upstream nodes and the bandwidth is split proportionally between relay and locally-generated traffic; however, the preference is given to the former. In ARC, in case an intermediate node overhears that the packets it sent previously are successfully forwarded again by its parent node, it will increase its rate by the constant α. Otherwise, it will multiply its rate by a factor β where $0<\beta<1$. ARC does not explicitly detect congestion and does not notify congestion explicitly; thus, it avoids using control messages. ARC improves fairness and is considered to be an energy-efficient congestion control algorithm for WSNs. However, it should be pointed out that ARC rate adjustment scheme introduces packet loss.

3.3.1.1.2. CODA. Wan et al. (2003) proposed congestion detection and avoidance (CODA) protocol for controlling congestion in WSNs. CODA amalgamated the present and past channel load and the level of buffer load to detect congestion at the intermediate sensor nodes. This protocol makes use of two strategies to control congestion: open-loop hop-by-hop backpressure and closed-loop multi-source traffic regulation (Wan et al., 2003). In open-loop hop-by-hop backpressure used for transient congestion, a node broadcasts back-pressure messages upstream towards source nodes to reduce their transmission rates. In closed-loop multi-source regulation which is based on end-to-end acknowledgment and is used for persistent congestion, the sink asserts congestion control over many source nodes. To regulate data transmission rate, sink node transmits ACK packets towards nodes. In CODA, control packets such as ACK and backpressure consume additional energy of the sensor nodes. CODA does not provide flow fairness and differentiates services into multiple classes of traffic. CODA adjusts rate through AIMD mechanism which often leads to packet loss. CODA carries out unidirectional congestion control, increases timelines but does not take reliability into consideration.

3.3.1.1.3. CCF. In congestion control and fairness (CCF) protocol, (Ee and Bajcsy, 2004) congestion detection depends on packet service time and every sensor node controls the rate of its downstream nodes. This method uses a scalable and distributed algorithm to conduct upstream congestion control which ensures the fair delivery of the packets to the central station as well as congestion elimination. CCF formulates congestion control and determines the number of downstream nodes, average transmission rate of the packets and the production rate in each sensor. CCF precisely adapts traffic rate according to packet service time and fair packet scheduling algorithms. CCF controls congestion hop-by-hop and each node uses exact rate adjustment based on available service rate and child node number. Rate adjustment in CCF is a function of packet service time which can result in low utilization when some sensor nodes do not have enough traffic or significant packet error rate. However, CCF does not take current queue utilization into account which results in the increased queuing delays and frequent buffer overflows as well as increased retransmissions.

3.3.1.1.4. FUSION. Hull et al. (2004) introduced Fusion as a method for mitigating congestion; this method detects congestion by means of queue lengths. Moreover, Fusion makes use of hop-by-hop flow control, rate limitation and a prioritized MAC technique to handle congestion. As a matter of fact, if the packets of nodes are intended to be dropped downstream, hop-by-hop flow control stops them from transmitting packets because of insufficient buffer spaces. When compared with other uncongested nodes, it is observed that this priority is accomplished through decreasing the random back-off timer of congested nodes. Rate limitation metrics of traffic are accepted into a network to prevent unfairness towards sources located far from the sink. A prioritized CSMA-based MAC ensures that the congested nodes should receive prioritized access to the channel. As a result, it should be maintained that FUSION optimizes fairness and has a good throughput; nevertheless, it is only effective in case all nodes have the same traffic load (Pang et al., 2008). Moreover, fusion is not able to guarantee an optimal transmission rate for those nodes which are both fair and efficient.

3.3.1.1.5. CONSISE. Vedantham et al. (2007) proposed an adaptive, explicit rate control method, referred to as congestion control from sink to sensors (CONSISE). This method adjusts the downstream transmission rate at each of the sensor nodes so as to utilize the available network bandwidth. It should be noted that CONSISE is regarded as a highly scalable and easily implementable method which has remarkable performance advantages; that is, it uses resources efficiently with minimal overheads. In CONSISE, as a node receives a packet from an upstream node, it will piggyback the respective information based on its current transmission rate and its node identifier. Moreover, as each downstream node receives a packet, it updates the information with respect to the number of packets received from a specific node. At the expiry of a periodic timer, a node specifies its transmission rate and gives explicit feedback to the upstream node.

Scheuermann et al. (2008) put forth a hop-by-hop congestion control protocol designed for the special features of the shared medium. This proposed congestion control protocol ensures that changing medium conditions are replied rapidly and that the overhead is negligible.

3.3.1.1.6. FACC. Yin et al. (2009) proposed Fairness-Aware Congestion Control (FACC) which is intended to control congestion and maintain approximately fair bandwidth allocation for different flows. Near-source nodes maintain a per-flow state and allocate an approximately fair rate to each passing flow. In contrast, near-sink nodes do not have to keep a per-flow state and use a lightweight probabilistic dropping algorithm according to queue occupancy and hit frequency. Indeed, it can be mentioned that FACC optimizes throughput, packet loss, energy efficiency and fairness.

3.3.1.1.7. CADA. Fang et al. (2010) presented a scheme for congestion avoidance, detection and alleviation (CADA) in WSNs.

This scheme optimizes energy consumption and information loss problems. By exploiting data features, a few representative sensor nodes are selected from those in the event area as data sources: as a result, source traffic can be mitigated and controlled proactively. Consequently, the potential congestion is avoided. When congestion takes place unavoidably as a result of traffic emergence, it will be detected immediately by the hotspot node based on a combination of buffer occupancy and channel utilization. Moreover, congestion is alleviated reactively by either dynamic traffic control or source rate regulation according to specific hotspot scenarios. In other words, it can be mentioned that CADA optimizes throughput, energy consumption and average end-to-end delay.

3.3.1.1.8. ECODA. Enhanced congestion detection and avoidance (ECODA) was developed to use dual buffer thresholds and weighted buffer difference for detecting congestion in WSNs (Tao and Yu, 2010). ECODA includes three mechanisms: (1) in the first strategy, dual buffer thresholds and weighted buffer difference are used as to detect congestion; (2) the second strategy makes use of flexible queue scheduler based on packet priority; (3) the control scheme of bottleneck node-based source transmission rate is used as the third strategy in case of persistent congestion. Indeed, ECODA uses hop-by-hop congestion control scheme for transient congestion.

Brahma et al. (2012) put forth a distributed congestion control algorithm for tree-based communications in WSNs; this algorithm assigns a *fair* and *efficient* transmission rate to each node. Also, each node controls and monitors its aggregate output and input traffic rate. With respect to the difference between input and output traffic rate, a node makes a decision on whether to increase or decrease the bandwidth; such a decision to increase or decrease the bandwidth is allocated to the flow that originates from itself and its neighboring nodes.

3.3.1.2. Comparing popular traffic control mechanisms. In this section of the paper, popular traffic control protocols are compared with each other with respect to the following factors: main idea, advantages and disadvantages. Table 1 demonstrates these comparisons.

3.3.2. Resource control mechanisms

In this method, affected sources take advantage of redundant deployment of nodes in the network. For maintaining the rate, this method employs nodes that are not involved in the current flow for packet transmission. Indeed, the use of other paths to the sink and hence, the consequent increase of the final network throughput are regarded as the merits of this technique. Obviously, nodes in this method cannot arbitrarily decide which flows should be rejected and whether other nodes should be randomly selected to join the rejected flows. Thus, before applying a source control method, some parameters such as congestion type and application type should be considered (Sergiou et al., 2013).

3.3.2.1. Popular resource control mechanisms. In this section, some important and major resource control mechanisms of congestion control in WSNs are presented, reviewed and the discussed mechanisms are compared.

3.3.2.1.1. TARA. Jaewon et al. (2007) proposed Topology Aware Resource Adaptation (TARA). It was aimed at adapting additional recourses of the network and alleviating intersection hot spots in case of congestion. In fact, TARA considers buffer occupancy and channel load to detect congestion. Nevertheless, it should be noted that TARA has remarkably high overhead and is not scalable. It makes use of distributor and merger nodes to alleviate congestion. Whereas the distributor distributes the traffic originating from the hotspot between the original path and the detour path, the merger merges the two flows. When congestion occurs, traffic is deflected from the hotspot through the distributor node along the detour and reaches the merger node. However, inasmuch as TARA needs the knowledge of whole network topology, it is not feasible for large-scale sensor networks.

Table 1
Popular traffic control protocols and their features.

Protocol	Key idea	Advantages	Disadvantages
ARC (Woo and Culler, 2001)	Each node estimates the number of upstream nodes and the bandwidth is split proportionally between route-through and locally generated traffic	Avoids use of control messages	Increases packet loss
CODA (Wan et al., 2003)	Receiver-based congestion detection, open-loop hop-by-hop backpressure, closed-loop multi-source regulation	Energy efficient, reducing the energy tax with low fidelity, eliminates flow starvation	Not reliable, no differentiated services to multiple class of traffic, rate adjustment leads to packet loss
CCF (Ee and Bajcsy, 2004)	Controls congestion in a hop-by-hop manner and each node adjusts rate based on its available service rate and child node number	Distributed and scalable algorithm, no additional control packets reliable, provides fair rate assignment	Low throughput, low utilization, queuing delay, buffer overflows, increased retransmission
FUSION (Hull et al., 2004)	Rate limit, contention period reduction	Fairness, improves performance, prioritized access to wireless medium	Cannot guarantee an optimal transmission rate for the nodes that is both fair and efficient, broadcast message not guaranteed to reach source, difficult to find the threshold value
CONSISE (Vedantham et al., 2007)	Sensor nodes are able to determine and adjust their sending rate based on the congestion level at the end of each epoch	Highly scalable, easy to implementation, improves performance	It controls congestion from sink to sensors instead from sensor to sink
Scheuermann et al. (2008)	Provides hop-by-hop congestion control protocol that has been tailored to the specific properties of the shared medium	Low overheads	Unfairness
FACC (Yin et al., 2009)	Allocates a faire share of available bandwidth to each active flow according to its generating rate	Improves the number of dropped packets, throughput and energy consumption	Probabilistic dropping packet
ECODA (Tao and Yu, 2010)	Use dual buffer thresholds and weighted buffer difference, flexible queue scheduler for packets scheduling	Energy efficient, reduced delay, better QoS, better throughput and fairness	Lack of packet recovery
CADA (Fang et al., 2010)	The congestion level is measured by an aggregation of buffer occupancy and channel utilization	Improves throughput, energy consumption, end to end delay	Unfairness
Brahma et al. (2012)	Distributed CC algorithm for tree based communications	Fair and efficient transmission rate Flexible design	It is operational for tree-based topology

3.3.2.1.2. LACAS. Misra et al. (2009) proposed Learning Automata based on Congestion Avoidance Scheme (LACAS) protocol. This protocol is intended to keep data packet arrival rate and data packet service rate equal in all intermediate nodes. LACAS uses the drop rate of packets in intermediate nodes as an index to detect congestion. After detecting congestion in network, the protocol tries to use other nodes as intermediate nodes to relay some part of the congested traffic. However, it should be noted that LACAS does not consider link level congestion and by forwarding the traffic in multi-hop paths, it causes the problem of high energy consumption in sensor nodes. An important feature of LACAS is that it intelligently learns from the past behaviors and controls congestion efficiently.

Congestion-aware and Rate-controlled Reliable Transport (CRRT) (Alam and Hong, 2009) uses MAC retransmission efficiently to increase one-hop reliability and end-to-end retransmission for loss recovery. Based on rate assignment policy of application, CRRT assigns the rate centrally to the source.

Pilakkat and Jacob (2009) presented a cross-layer design for congestion control in WSNs. The multiple access communication for WSNs is assumed to be Ultra-Wide Bandwidth (UWB) Time-Hopping Spread-Spectrum (TH-SS) impulse radio. Joint congestion and power control was proposed and formulated as a network utility maximization problem which is solved by distributed iterative algorithms for flow rate adaptation and power adaptation on every link. Power control algorithm allocates the right amount of power at the right nodes to alleviate the bandwidth bottlenecks while it maintains the signal to interference-and-noise ratio above a given threshold for every link. Hop-by-hop approach reduces buffer size requirement significantly under high feedback delays.

3.3.2.1.3. HTAP. Sergiou et al. (2013) introduced the Hierarchical Tree Alternative Path (HTAP) hop-by-hop congestion control protocol in WSNs. HTAP is a simple, efficient and scalable resource control which produces dynamic alternative paths to the sink in order to mitigate congestion. HTAP includes four different schemes: topology control, hierarchical tree creation, alterative path creation and handling of powerless nodes. In topology control scheme, each node creates and updates its neighbor table. In hierarchical tree production, a hierarchical tree is produced in which source node is regarded as its root. Using two-way handshaking method, the receiver node informs the transmitter node of its congestion level. In alternative path production, the transmitter node selects a node from its neighbor table that has no congestion. In the final part, if the battery of a sensor node is deplete, the neighbor table of will be updated. Alternative path does not employ nodes which are not in the initial path from the source to the sink. HTAP employs an adaptive “congestion threshold” which enables it to avoid transient congestion situations. The chief benefit of HTAP algorithm lies in its simplicity which results in minimal overhead.

3.3.2.1.4. Flock-CC. Antoniou et al. (2013) proposed Flock-based Congestion Control (Flock-CC). Flock-CC utilized birds' behavior to design a robust, scalable and self-adaptive congestion control protocol for WSNs. Flock-CC made use of a swarm intelligence paradigm which was inspired by the collective behavior of bird flocks. The rationale behind Flock-CC is to ‘guide’ packets (birds) to form flocks and flow towards the sink (global attractor) while it tries to avoid congestion regions (obstacles). The motion direction of a packet flock is influenced by repulsion and attraction forces between packets and the field of view and the artificial magnetic field in the direction of the artificial magnetic pole (sink). Inasmuch as Flock-CC requires minimal information exchange, it is simple to implement at individual nodes. Furthermore, it displays global self properties and emergent behavior which are accomplished collectively without explicitly programming these properties into individual packets. This scheme dynamically balances the existing load by effectively exploiting available network resources and moving packets to the sink. Furthermore, Flock-CC improves QoS parameters such as packet delivery ratio, packet loss, delay and energy consumption with different traffic loads. Moreover, Flock-CC achieves robustness against failing nodes and scalability.

3.3.2.1.5. WCCP. Mahdizadeh Aghdam et al. (2014) put forth a novel content-aware cross layer WMSN Congestion Control Protocol (WCCP). In this protocol, features of multimedia content are taken into consideration. It utilizes Source Congestion Avoidance Protocol (SCAP) in source nodes and Receiver Congestion Control Protocol (RCCP) in intermediate nodes. SCAP predicts Group of Picture (GOP) size to detect congestion in the network and avoids congestion by adjusting the transmission rate of source nodes and distribution of the departing packets from the source nodes. Also, RCCP examines and observes the queue length of the intermediate nodes to detect congestion in both monitoring and event-driven traffics. Moreover, to improve the quality of the received video in base stations, WCCP keeps I-frames and ignores other less

Table 2
Popular resource control protocols and their properties.

Protocol	Key idea	Advantages	Disadvantages
TARA (Jaewon et al., 2007)	Adopts different traffic multiplexing strategies depending on specific topology	Measures not only the buffer occupancy but also the channel loading in order to detect congestion, provides fidelity satisfaction and energy conservation	High overhead for a large-scale network, not scalable
LACAS (Misra et al., 2009)	Avoids congestion by using a learning, automata based approach	Improves performance intelligently learn from the past	Pure traffic reduction could impose a negative impact on data fidelity, high energy consumption, does not consider link-level congestion
CRRT (Alam and Hong, 2009)	Assigns the rate to the source based on the rate assignment policy	Increases reliability	High energy consumption
Pilakkat and Jacob (2009)	Uses congestion and power control jointly	Delete bottleneck, controls power consumption	Increases end-to-end delay
Flock-CC (Antoniou et al., 2013)	Guides packet to form flocks and flow toward the sink	Robust again failing node, scalable, self-adapting, improves PDR, delay and energy consumption, simple implementation	Does not guarantee fairness
HTAP (Sergiou et al., 2013)	Creates dynamic alternative paths to the sink	Simplicity, minimum overhead	Not energy efficient
Domingo (2013)	Provides a biologically inspired congestion control protocol for UWSNs	Distribute algorithm, provides flow fairness	Does not guarantee reliability
WCCP (Mahdizadeh Aghdam et al., 2014)	Uses source congestion avoidance protocol in source node and a receiver congestion control protocol in intermediates node	Improves the network performance and quality of receive video in sink	Not energy efficient

important frame types of the compressed video in the congestion situations. WCCP remarkably optimizes network performance and the quality of the received video in the sink nodes.

Domingo (2013) introduced a biologically-inspired congestion control protocol for underwater WSNS (UWSNs) based on the capability of marine communities to terminate with phytoplankton blooms and move the system back to equilibrium between species. This algorithm distinguishes packet losses caused by congestion from packet losses related to high link error rates. It obviates flow starvation and provides flow fairness. The channel impacts of underwater propagation on packet losses are captured, shadow zones are detected and the throughput of the flows from different nodes at the receiver is restored even with channel fading.

3.3.2.1.6. DAlPAS. Sergiou et al. (2014) proposed a novel congestion control protocol, dynamic alternative path selection protocol (DAlPaS) in WSNs. DAlPaS is regarded as a completely dynamic, distributed and lightweight scheme; it was intended to diminish networks congestion probability. In line with this purpose, it proposed a soft-stage technique. This protocol was designed so that each node utilizes soft-stage scheme to serve only one flow. Hence, in case each node serves only one flow, the probability of buffer-based congestion will diminish. If this procedure is not accomplished, DAlPaS algorithm makes use of its hard-stage scheme. By doing so, data flows are obliged to change their path so that the receiving node is not congested.

3.3.2.2. The comparison of resource control protocols and their properties. In this section of the paper, most popular resource control mechanisms are compared. In fact, use of other backup paths from source to sink and the enhancement of final network throughput are regarded as the major merits of this scheme. Table 2 demonstrates the key features and points, merits and demerits of resource control protocols.

3.3. *Queue-assisted mechanism*

Queue-assisted protocols mainly focus on queue length of the nodes and use a simple rate adjustment technique such as AIMD to keep the queue length of nodes as low as possible. However, it should be maintained that due to the simple nature of these protocols, they do not have high energy consumption.

3.3.1. Popular queue-assisted mechanism. In this section, a number of significant and well-known queue-assisted mechanisms designed for controlling congestion in WSNs are reviewed and compared with each other.

3.3.1.1. IFRC. Rangwala et al. (2006) introduced the Interference Aware Fair Rate Control protocol (IFRC). IFRC is regarded as a distributed rate allocation scheme which uses queue size to detect congestion and shares the congestion state through overhearing. Furthermore, IFRC has major problems such as sophisticated parameter tuning for stability. In IFRC, parameters and thresholds must be selected before a network can be deployed. Also, in this protocol, nodes are obliged to collect rate information from their neighboring nodes which increase processing overhead and energy consumption.

3.3.1.2. DPCC. Zawodniok and Jagannathan (2007) introduced decentralized, predictive congestion control (DPCC) for WSNs. DPCC includes an adaptive flow and adaptive back-off interval selection schemes which act jointly with energy efficient, distributed power control (DPC). This protocol uses queue utilization and embedded channel estimator algorithm to detect the onset of congestion in DPC. Then, an adaptive flow control scheme chooses an appropriate rate which is executed by the adaptive back-off interval selection scheme. An optional adaptive scheduling protocol updates weights of each packet to ensure that weight fairness is realized in congestion. Closed-loop stability of the proposed hop-by-hop congestion control is demonstrated by using the Lyapunov-based approach. DPCC uses weights associated with flows to fairly allocate resources during congestion. By adding an optional, dynamic weight adaptation algorithm, weighted fairness can be guaranteed in dynamic environments.

3.3.3.1.3. QCCP-Ps. Yaghmaee and Adjeroh (2008) introduced Queue-based Congestion Control Protocol with Priority Support (QCCP-Ps). It makes use of queue length as a congestion degree indicator. QCCP-Ps controls congestion with packet priority based on node priority for a WSN. QCCP-PS also optimizes priority-based congestion control protocol (PCCP) by handling the queue more finely; however, it does not have any mechanism for controlling prioritized heterogeneous traffic in a network. The transmission rate of each traffic source in QCCP-PS increases or decreases based on its congestion degree and its priority index. Rate adjustment for each traffic source depends on its priority index as well as its current congestion degree.

Michopoulos et al. (2010) presented a congestion control mechanism in which the buffer in each node is adjusted based on the transmitting downstream nodes to minimize packet drop. This mechanism adapts and adjusts nodes' forwarding rate automatically to avoid packet drops which result from congestion. This algorithm manages to sort out the fairness problem through allocating equal bandwidth to the sources.

3.3.3.1.4. CCTF. Zarei et al. (2011) proposed congestion control protocol based on trustworthiness of nodes in WSNs using fuzzy logic (CCTF). Using CCTF, each node reduces the impact of malfunctioning neighbor by dropping valueless packets and increasing buffer capacity. Consequently, the chance of network congestion diminishes.

3.3.3.1.5. GMCAR. Grid-based Multipath with Congestion Avoidance Routing (GMCAR) is an efficient grid and QoS-based routing protocol which has been proposed by Banimelhem and Khasawneh (2012). In each grid, the master node is responsible for delivering the data generated by any node in that grid and for routing the data received from other master nodes in the neighbor grids. For each master node, multiple diagonal paths connecting the master node to the sink are stored as routing entries in the routing table of that node. Master nodes check the occupancy levels of their buffers as they are gradually filled up. For preventing congestion occurrence, once the buffer occupancy exceeds a predefined threshold (O_{th}), incipient congestion is detected and the avoidance mechanism starts. The avoidance scheme is based on diverting the incoming traffic to the other available paths. The congested node creates a timer and broadcasts "route invalidate" message to the neighboring nodes.

3.3.3.1.6. HOCA. Rezaee et al. (2014) proposed a data centric congestion management protocol using Active Queue managements (AQM) (Athuraliya et al., 2001). HOCA was introduced for healthcare applications with respect to the inherent characteristics of these applications. In this protocol, researchers focused on end-to-end latency, energy consumption, network lifetime and fairness. HOCA avoids congestion in routing phase using multipath and QoS-aware routing. In case congestion cannot be avoided, it will be mitigated via an optimized congestion control algorithm (Rezaee et al., 2014). HOCA considers two kinds of traffic: sensitive (to transfer high priority data) and non-sensitive (to transfer normal traffic). HOCA has the following phases: (1) request dissemination which is performed by the sink, (2) event occurrence report which is performed using packets that are forwarded from sensors located on patients' body to the sink, (3) route establishment, (4) data forwarding and rate adjustment in case of congestion occurrence.

3.3.3.2. Comparing the queue assisted protocols. Table 3 lists the popular queue assisted protocols and their properties.

3.3.4. Priority-aware mechanisms

3.3.4.1. Well-known priority-aware protocols. In this section, a number of well-known priority-aware mechanisms of congestion control in WSNs are reviewed and their mechanisms are compared with one another.

3.3.4.1.1. PCCP. Wang et al. (2007) introduced PCCP. It is a priority-aware upstream congestion control protocol that measures a congestion degree as the ratio between packet arrivals and packet service time. In contrast with the AIMD technique, PCCP uses rate adjustment algorithm. It supports fairness in weighting sensor nodes. PCCP makes use of different degrees of priority indexes; that is, a sensor node with a higher priority index uses more bandwidth and injects more traffic. PCCP was aimed at operating under both single path routing and multipath routing scenarios. It includes intelligent congestion detection according to packet inter-arrival time and packet service time. To the best of the researcher's knowledge, this procedure has not been employed in other previous techniques. Indeed, it uses implicit congestion notification to avoid transmission of additional control messages. Thus, it optimizes energy efficiency. PCCP estimates congestion degree as the ratio of packet inter-arrival time along over packet service time. Based on the introduced congestion degree and node priority index, PCCP utilizes a cross-layer optimization and imposes a hop-by-hop approach to control congestion. However, it should be mentioned that the lack of packet recovery is regarded as shortcoming of PCCP. On the whole, PCCP results in lower buffer occupancy, high link utilization, low packet utilization and low packet delay.

3.3.4.1.2. CL-APCC. Cross-Layer Active Predictive Congestion Control (CL-APCC) scheme (Wan et al., 2009 was aimed at improving the performance of networks. It employed queuing theory to examine data flows of a single-node according to its memory status and analyzed the average occupied memory size of local networks. It also investigates the current data change trends of local networks to forecast and actively adjust the sending rate of the node in the next period. To guarantee network fairness and timeliness, the IEEE 802.11 protocol was updated based on waiting time, the number of a node's neighbors and the original priority of data packets which dynamically adjusts the sending priority of the node.

3.3.4.1.3. TLP. Yaghmaee and Adjeroh (2009) proposed a scheme with exponential weighted priority-based rate control (EWPBRC), the transmission data exhibit massive variations and a large error between input transmission rate and estimated transmission rate for each sensor node, resulting in inconsistent network resource allocation. The traffic load parameter was a fixed value to yield such that the delay and loss probability for the WMSN is increased.

3.3.4.1.4. ACT. Lee and Jung (2010) presented adaptive compression-based congestion control technique (ACT) for reducing packet in case congestion occurs. The compression techniques used in ACT are discrete wavelet transform (DWT), adaptive differential pulse code modulation (ADPCM) and run-length coding (RLC). This technique first

Table 3
Well-known queue-assisted protocols and their characteristics.

Protocol	Key idea	Advantages	Disadvantages
HOCA (Rezaee et al., 2014)	Mitigating and controlling congestion using multipath routing	Avoids congestion, make use of two routing tables for sensitive and non-sensitive data	Congestion is not avoided for non-sensitive data
IFRC (Rangwala et al., 2006)	Adjusting outgoing rate on each link based on AIMD	Fair bandwidth allocation	Threshold value selection
QCCP-Ps (Yaghmaee and Adjeroh, 2008)	Adjusts the traffic rate of each node based on its degree of congestion, and thus can avoid unnecessary packet loss	Reliable and fair transport protocol, low packet loss, efficient congestion control	It does not have any mechanism for handling prioritized data
GMCAR (Banimelhem et al., 2012)	Grid and QoS based routing protocol	Energy efficient	Gridding and master node selection overhead
DPCC (Zawodniok and Jagannathan, 2007)	Rate based control and back off interval selection	Prediction of congestion, energy efficient, decentralized	Buffer overflows and significant drop rate
Michopoulos et al. (2010)	The buffer in each node is adjusted according to the transmitting downstream nodes	Minimizes packet drop, automatically adjusts a node's forwarding rate, fairness	Not energy efficient
CCTF (Zarei et al., 2011)	CC protocol based on trustworthiness of nodes using fuzzy logic	Drops valueless packets and increases the buffer capacity	Increases packet loss

Table 4
Popular priority aware protocols and their characteristic.

Protocol	Key idea	Advantages	Disadvantages
PCCP (Wang et al., 2007)	Uses packet arrival time and packet service time to detect congestion	Achieves high link utilization and flexible fairness with small buffer size; reduces packet loss, improves energy efficiency, provides lower delay	Does not consider how to choose priority index for each node, queuing delay, buffer overflows, increased retransmission
CL-APCC (Wan et al., 2009)	Cross-layer active predictive congestion scheme improving the performance	Fairness and timeliness	Not energy efficient
ACT (Lee and Jung, 2010)	Adaptive compression based CC technique for packet reduction in case of congestion	The queue is controlled adaptively according to the congestion state	Not energy efficient
DPCC (Heikalabad et al., 2011)	Predicts congestion in sensor nodes and broadcast traffic on the entire network fairly and dynamically	Increase throughput, reduces packet loss fairness, low control overhead	Not energy efficient
Chen et al. (2014)	Fuzzy logical based controller with an exponential weighted priority based rate control	Improves quality of service optimizes traffic load	Large error between input transmission rate and estimated transmission rate

transforms data from time domain to frequency domain; next, it uses ADPCM to reduce the magnitude of data; consequently, it reduces the number of packets by means of RLC before transferring data to the source node. Since DWT categorizes data into four groups with different frequencies, it introduces DWT for priority-based congestion control. ACT assigns priorities to these data groups in an inverse proportion to the respective frequencies of the data groups and defines the quantization step size of ADPCM in an inverse proportion to the priorities. RLC generates a smaller number of packets for a data group with a low priority. In the relaying node, the ACT reduces the amount of packets by increasing the quantization step size of ADPCM in case of congestion.

3.3.4.1.5. DPCC. Heikalabad et al. (2011) introduced dynamic prediction congestion control (DPCC). It was aimed at predicting congestion in sensor nodes and broadcasting traffic on the entire network fairly and dynamically. This protocol is intended to enhance throughput and reduce packet loss as well as ensuring that distributed priority is fair and control overhead is low. This protocol encompasses three components: backward and forward nodes selection (BFS), predictive congestion detection (PCD) and dynamic priority-based rate adjustment (DPRA). These components are responsible for precise congestion discovery and weighted fair congestion control. Node i selects a forwarded node for itself according to received rate adjustment values from the set of forwarded nodes of i. The node i selects one as a forward node whose received rate value from it is maximum. Then, node i sends notification to the selected forwarded node. To enhance throughput, the other forwarded nodes of node i which are not selected as a forwarded node of this node adjust the new rates for their other backward nodes. To detect congestion, a congestion index (CIi) reflecting the current congestion level at each sensor node i is specified based on its unoccupied buffer size (UBSi) and traffic rate (Cerpa et al.) at MAC layer.

3.3.4.1.6. FLC. Chen and Lai (2014) proposed a novel fuzzy logical controller (FLC) related to traffic load parameter (TLP) schemes with an exponential weighted priority-based rate control (EWPBRC). The purpose of this scheme was to measure the output transmission rate of the parent node and then assigns an appropriate transmission rate with regard to the traffic load of each child node and based on different amounts of data transmission. Moreover, they proposed a scheme that was able to control different transmission data types effectively so that QoS requirements of a system can be achieved while decreasing network resource consumption.

A model based on transmission priority has been proposed to mitigate network transmission congestion in a WMSN. In terms of transmission rate, the fixed traffic load parameter (TLP) scheme was used for adjustment purposes. Table 4 illustrates well-known priority-aware protocols and their characteristics.

3.3.4.2. Reliable data transport protocols. Indeed, reliable data transport protocol refers to a diverse type of transport layer protocol which focuses on the reliability of data transmission. However, inasmuch as they control congestion, they are included within the category of congestion control mechanisms. It can be argued that an efficient transport protocol should deliver messages reliably, consume energy efficiently should provide high-quality services and last but not least control congestion. In the following part, common reliable data transport protocols are reviewed and discussed.

3.3.4.2.1. PSFQ. Wan et al. (2002) presented pump slowly fetch quickly (PSFQ) protocol for WSNs. It supports a simple, robust and scalable transport for different reliable data applications. PSFQ includes three protocol components: message relaying (pump operation), relay-initiated error recovery (fetch operation) and selective status reporting (report operation). It is used to distribute data from a source node by pacing data at a relatively slow speed (pump slowly); nevertheless, it allows nodes which have experienced data loss to fetch any missing segments from immediate neighbor nodes aggressively (local recovery, fetch quickly). In this case, packet delivery might fail. Since PSFQ used only NACK not ACK, it suffers from large delay; hence, it cannot detect the loss of single packets. In PSFQ, hop-by-hop recovery with cache will need more buffer.

3.3.4.2.2. ESRT. Akan and Akyildiz (2005) proposed event-to-sink reliable transport (ESRT), a fairness congestion control protocol for WSNs. ESRT allocates transmission rates to sensors and the sink node and centrally computes the rate of allocation. ESRT monitors the local buffer level of sensor nodes and, in case the buffer overflows, it sets a congestion notification (CN) bit in the packets it forwards to the sink. If a sink receives a packet with CN = 1, it infers congestion and broadcasts a control signal informing all sources to reduce their common reporting frequency. ESRT has several drawbacks: firstly, an event occurrence transmission can be disrupted by this high powered congestion signal. This scheme always regulates all sources regardless of where the hotspot occurs in the sensor network. It does not consider different types of events requiring different levels of reliability. ESRT regulates report frequency of all sensors using the same value and uses a one-hop channel with high power. It considers reliability and energy-conservation in congestion control.

3.3.4.2.3. SenTCP. Wang et al. (2005) proposed SenTCP as an open-loop hop-by-hop congestion control protocol. This protocol uses average packet service time, average packet inter-arrival time and buffer occupancy ratio to estimate the current local congestion degree at each intermediate sensor node. Each intermediate sensor node gives out a feedback signal backward periodically. This feedback signal carries local congestion degree and queue length ratio. Also, this signal is used for the neighboring sensor

Table 5
Popular reliable data transport protocols and their properties.

Protocol	Key idea	Advantages	Disadvantages
PSFQ (Wan et al., 2002)	Distributes data from a source node at a relatively slow speed pump slowly) but it allows nodes to fetch any missing data from immediate neighbor nodes very aggressively (fetch quickly)	Simple, robust and scalable	Increases packet loss, has large delay, more buffer is needed for hop-by-hop recovery with cache, cannot detect lost single packets
ESRT (Akan and Akyildiz, 2005)	Reliable transport scheme which maintains operation in state OOR (Optimal Operating Region)	Event-to-sink reliability, high energy efficiency, self-configuring nature	All sensor nodes are controlled at once, it is unfair and does not support efficient rate allocation, not scalable
SenTCP (Wang et al., 2005)	Uses average local packet service time and inter-arrival time to estimate congestion degree	Energy efficient, reduces packet loss, remove congestion quickly, mitigates differentiating congestion	Does not guarantee reliability
XLP (Vuran and Akyildiz, 2010)	Performs hop-by-hop CC by exploiting local information in the receiver-contention	High utilization	It is not energy efficient

Table 6
Congestion control protocols for WSNs.

Protocol	Congestion detection	Congestion control	Congestion notification	Performance metrics	Data flow	Generic or cross-layer	Control pattern
ARC (Woo and Culler, 2001)	Queue length	Traffic control	Implicit	Energy efficiency, fairness	Event based and continuous	Generic	Hop-by-hop
PSFQ (Wan et al., 2002)	Queue length	Traffic control	Implicit	End-to-end delay, packet loss	Event based	Generic	Hop-by-hop
CODA (Wan et al., 2003)	Buffer occupancy and wireless channel load	Traffic control	Explicit	Energy tax, end-to-end delay, fairness	Continuous	Generic	End-to-end and Hop-by-hop
CCF (Ee and Bajcsy, 2004)	Packet service time	Traffic control	Implicit	Fairness, energy conservation, utilization	Event based	Generic	Hop-by-hop
FUSION (Hull et al., 2004)	Buffer occupancy and wireless channel load	Traffic control	Implicit	Throughput, fairness, packet latency, network efficiency	Event based and continuous	Generic	Hop-by-hop
ESRT (Akan and Akyildiz, 2005)	Buffer occupancy	Traffic control	Implicit	Average energy consumption, fairness, reliability	Continuous	Generic	End-to-end
SenTCP (Wang et al., 2005)	Buffer occupancy/packet inter arrival time	Traffic control	Implicit	Energy conservation, throughput, packet loss ratio	Event based	Generic	Hop-by-hop
IFRC (Rangwala et al., 2006)	Queue length	Recourse control	Implicit	Throughput, goodput, packet delivery ratio	Continuous	Generic	Hop-by-hop
TARA (Jaewon et al., 2007)	Buffer occupancy and wireless channel load	Recourse Control	Explicit	Energy consumption	Continuous	Generic	Hop-by-hop
CONSISE (Vedantham et al., 2007)	Wireless channel load	Traffic control	Implicit	Latency, fairness	Query based	Generic	Hop-by-hop
Scheuermann et al. (2008)	Queue length	Recourse control	Implicit	Packet loss, energy efficient	Continuous	Generic	Hop-by-hop
DPCC (Zawodniok and Jagannathan, 2007)	Queue utilization, channel quality	Priority based recourse control	Implicit	Throughput, network efficiency	Query based	Generic	Hop-by-hop
PCCP (Wang et al., 2007)	Packet inter arrival time/ packet service time	Priority based traffic control	Implicit	Throughput, utilization, flexible fairness, energy efficiency	Event based	Generic	Hop-by-hop
QCCP-Ps (Yaghmaee and Adjeroh, 2008)	Queue length	Recourse control	Implicit	Packet loss, throughput, priority	Continuous	Generic	Hop-by-hop
LACAS (Misra et al., 2009)	Queue length	Learning automata adjust flows rate	Implicit	Energy consumption, throughput	Continuous	Generic	Hop-by-hop
CRRT (Alam and Hong, 2009)	Queue length	Recourse control	Implicit	End-to-end delay, reliability	Continuous	Generic	Hop-by-hop
Pilakkat and Jacob (2009)	Queue length	Recourse control	Implicit	Throughput, fairness	Continuous	Cross layer	Hop-by-hop
FACC (Yin et al., 2009)	Wireless channel load/ packet drop at the sink	Recourse control	Explicit	Throughput, fairness, packet loss	Event based	Generic	Hop-by-hop
Michopoulos et al. (2010)	Queue length	Recourse control	Implicit	Throughput, end-to-end delay	Event based	Generic	Hop-by-hop
CL-AP CC (Wan et al., 2009)	Queue length	Priority based recourse control	Implicit	End-to-end delay, energy consumption	Event based	Cross layer	Hop-by-hop
CADA (Fang et al., 2010)	Buffer occupancy and wireless channel load	Recourse and traffic control	Implicit	Energy efficiency, unfair, end-to-end delay, average per hop delay	Event based	Generic	Hop-by-hop
ECODA (Tao and Yu, 2010)	Dual buffer thresholds and weighted buffer difference	Traffic control	Implicit	Throughput, fairness, end-to-end delay	Continuous	Generic	Delay dependent
XLP (Vuran and Akyildiz, 2010)	Queue length	Traffic control	Implicit	Goodput, latency, energy consumption	Event based	Generic	Hop-by-hop
ACT (Lee and Jung, 2010)	Queue length	Priority based recourse control	Implicit	Energy consumption, end-to-end delay	Continuous	Generic	Hop-by-hop
CCTF (Zarei et al., 2011)	Packet Service time		Implicit	End-to-end delay, throughput	Continuous	Generic	Hop-by-hop
DPCC (Heikalabad et al., 2011)	Queue length	Recourse control	Implicit	Throughput, network efficiency, utilization	Continuous	Generic	Hop-by-hop
GMCAR (Banimelhem et al., 2012)	Queue length	Traffic control	Implicit	Energy efficiency, packet delivery ratio, end-to-end delay	Continuous	Generic	Hop-by-hop
Brahma et al. (2012)	Buffer occupancy	Traffic control	Implicit	Energy efficiency, throughput	Event based	Generic	Hop-by-hop
Domingo (2013(	Queue length	Recourse control	Implicit	Energy efficiency, throughput	Event based	Generic	Hop-by-hop
Flock-CC (Antoniou et al., 2013)	Buffer occupancy	Recourse control	Implicit	Packet delivery ratio, packet loss, energy tax, end-to-end delay	Event based	Generic	Hop-by-hop
HTAP (Sergiou et al., 2013)	Buffer occupancy	Recourse control	Implicit	End-to-end delay, packet loss, network power, unfairness	Event based	Generic	Hop-by-hop
Chen et al. (2014)	Queue length	Recourse control	Implicit	Packet loss, throughput	Continuous	Generic	Hop-by-hop
WCCP (Mahdizadeh Aghdam et al., 2014)	Queue length	Recourse control	Implicit	Packet delivery ratio, throughput, end-to-end delay	Continuous	Cross layer	Hop-by-hop
HOCA (Rezaee et al., 2014)	Queue length	Recourse control	Implicit	End-to-end latency, energy consumption, network lifetime and Fairness	Continuous	Generic	Hop-by-hop

Table 6 (*continued*)

Protocol	Congestion detection	Congestion control	Congestion notification	Performance metrics	Data flow	Generic or cross-layer	Control pattern
DalPAS (Sergiou et al., 2014)	Buffer occupancy and channel load	Recourse control	Implicit	Fairness, energy conservation	Continuous	Generic	Hop-by-hop

nodes to adjust their sending rate in the transport layer. The use of hop-by-hop feedback control can remove congestion quickly and reduce packet dropping, which in turn conserves energy. The use of hop-by-hop feedback control can remove congestion quickly and reduce packet dropping, which in turn conserves energy. SenTCP increases throughput and improves energy-efficiency. However, SenTCP does not consider reliability.

3.3.4.2.4. XLP. Vuran and Akyildiz (2010) presented XLP as a hop-by-hop local cross-layer congestion control protocol for WSNs, which is based on the sensor node's buffer occupancy. In XLP since the traffic injected by any node due to its router duty is controlled, the active congestion control is performed by controlling the rate of generated packets at node *i*. Since the local congestion control is specific to certain regions and may not apply to the entire event area, nodes inside a congested region may reduce their transmission rates. Thus, the local cross-layer congestion control exploits the local congestion control to maintain high network utilization. In XLP, the exchange of handshake messages will lead to overhead in WSNs.

3.3.4.3. Comparing of reliable data transport mechanisms. Table 5 shows the popular reliable data transport protocols and their properties.

4. Comparison of congestion control mechanisms for WSNs

Herein, the above-mentioned congestion control schemes are compared with one another. Table 6 briefly illustrates the comparison of congestion control mechanisms in WSNs. In this table, the following taxonomies are used to compare and contrast different congestion control mechanisms:

- Congestion detection
- Congestion notification
- Congestion mitigation
- Control pattern
- Performance evaluation metrics
- Data flow scheme
- Cross-layer or generic

Using performance metrics, the researcher analyzed the performance of different algorithms with regard to these metrics. Some remarkable and typical metrics used by the congestion control protocols are as follows: goodput, fairness, throughput, packet delivery ratio, end-to-end delay, average node energy consumption, packet loss rate, and network lifetime.

(a) **Goodput**: This metric indicates the best existing usage for intermediate sensor node resources. This metric is characterized as the bandwidth delivered to all receivers.
(b) Fairness: Fairness refers to the degree of variation in data transmission rate.
(c) Throughput: This parameter refers to the number of successfully received packets per unit time by the sink node.
(d) Packet delivery ratio: It is considered to be a remarkable metric for WSNs and refers to the number of successfully delivered packets divided by the total number of packets that are generated by source nodes.
(e) End-to-end delay: This kind of delay is measured as the required time at which a generated packet reaches the base station. End-to-end delay is deemed to be a performance metric which has an impact on QoS in WSNs. Real-time applications in WSNs are aimed at diminishing and minimizing this metric.
(f) **Energy consumption:** It indicates energy consumption of sensor nodes and measures the amount of energy consumed for sending and receiving packets. In WSNs, energy is a significant parameter and energy efficiency congestion control algorithms should consider this metric in all applications of WSNs.
(g) **Packet loss rate:** It is defined as the number of dropped packets divided by the total number of packet delivered to the sink in WSNs.
(h) **Network lifetime:** This metric is a function of energy consumption of sensor nodes.

5. Discussion

Increasing applications of WSNs in daily life and industry have framed newer challenges for the design and development of congestion control techniques in these different applications. It should be argued that in many applications of WSNs such as military, medical, target tracking and environmental monitoring which collect real-time data must be forwarded towards sink node without any timelines. In critical-mission applications, QoS parameters such as delay, packet loss, coverage and energy efficiency should be taken into consideration. On the other hand, inherent resource constrains and many-to-one communications lead to the production of congestion in WSNs. Congestion has a remarkable impact on the above-mentioned QoS parameters and consequently, it directly affects the throughput degradation of the network. Hence, it can be maintained that for prolonging network lifetime and improving application-dependent QoS parameters, an efficient congestion control technique is required in WSNs. In designing such an algorithm, researchers should consider queuing delay, queue length, energy efficiency and packet loss rate. The identified issues and challenges mentioned earlier in the paper with regard to congestion control methods in WSNs may help researchers in designing efficient congestion control protocols for WSNs. Based on the location and position at which congestion takes place, congestion can be categorized into the following types: (a) source congestion (hotspot near source), (b) intermediate node congestion, and (c) sink congestion (hotspot near the sink).

(a) **Source congestion:** Inasmuch as sensors are densely-deployed and there are event-based applications of WSNS, source congestion can be generated in the vicinity of the source sensor nodes. In this case, applying resource control algorithms can be a correct solution for this type of hotspot.
(b) **Intermediate node congestion**: Since data flows in tree-like architectures intersect with each other, the area around the intersection is considered to be a hotspot. Thus, each intermediate

sensor node in this architecture will be affected by this type of congestion. Consequently, the combination of resource control scheme and traffic control techniques will be of high significance in congestion control mechanisms.

(c) **Sink congestion**: One of the most important challenges in WSNs is the congestion or hotspot near the sink which is attributed to many-to-one data transmission characteristic of WSNs. In this type of congestion, the energy of nodes near the sink is exhausted; hence, energy hole problem is created. An appropriate method for alleviating sink congestion is to use multiple sinks in WSNs in order to balance the traffic between these sinks.

The selection of congestion control techniques depends on the nature of WSN applications. In other words, it should be noted that WSNs applications have an impact on the control applied to the data traffic in WSNs. Based on data delivery methods, all WSN applications can be classified as follows: (a) event-based applications, (b) continuous applications, (c) query-driven applications and (d) hybrid applications.

(a) **Event-based applications**: In this type of application, WSN operates under light load but specifications such as unpredictable responses to suddenly detected events can generate large data packets. Due to mission-critical and real-time nature of the generated data traffic, congestion control is considered to be a vital and important operation in event-based applications. Thus, data traffic generated from the sensors near the detected event or phenomena should be delivered without any additional delay to sink node for further operations. Examples for this type of applications are: target tracking, battlefield surveillance, fire detection and wild life detection in forest.
(b) **Continuous-driven applications (time-driven or streaming):** In this type of WSN applications, sensor nodes send the collected data to the sink in continuous schemes. In multimedia-based applications of WSNs such as health-care monitoring and video/voice applications, uncontrolled use of constraint resources and increasing the rate of data reporting might result in WSN congestion.
(c) **Query-**driven applications: In this kind of applications, the sink sends query to sensor nodes and the sensing nodes respond (answer) to the query of sink. In this state, transient congestion arises.
(d) **Hybrid applications:** WSNs have recently attracted researchers' attention and newer applications. With combination of WSN applications and IOT (internet of things) based systems (Atzori et al., 2010), in the future, this kind of application is expected to be common and widespread. It should be noted that, in new applications, design and implementation of congestion control protocols are affected by newer challenges and problems.

It should be pointed out that, in case there is a transient overload situation, solutions following traffic control protocol can be regarded as more efficient. On the other hand, resource control techniques are more effective with respect to persistent high load demands. Although traffic control is less complicated and less costly, the reduction of source data at the time the monitored event is taking place will make it inappropriate for a significant number of applications.

It can be argued that since many factors should be taken into consideration in designing and implementing a resource control algorithm, it is a demanding process. Furthermore, inasmuch as routing loops might be produced and data packets might not be delivered to the sink, allowing nodes to select the next hop randomly or an alternative path only based on buffer occupancy level will become devastating. As a result, it should be discussed that for selecting the next neighboring node to transmit data, the congestion control protocol should consider both parameters of buffer occupancy level and wireless channel load.

In event-based applications, when an event occurs, sensor nodes identifying the event transmit urgent packets massively to the sink reporting the event; as a result, congestion will be produced. On the other hand, an adversary or malicious node might falsely try to flood the network with other urgent packets; as a result, the transmission of erroneous packets will cause a delay in the delivery of honest packets. Consequently, that event cannot be properly covered and reported and hence, the network mission will fail. It needs to be noted that the malicious nodes should be detected and distinguished from honest nodes in event-based applications.

6. Conclusion and directions for future research

6.1. Conclusion

Based on the presented arguments and discussions, it was argued that congestion control is one of the most important challenges in WSNs. The review of the related literature indicated that event-driven nature of WSNs and their inherent constrains are the main cause of unpredictable network load. Any increase in network congestion can bring about energy waste, throughput reduction and packet loss which corroborate the consequences of network congestion on network life time and the efficiency of energy consumption.

This paper presented a comprehensive survey and review of popular congestion control techniques in WSNs and outlined the features, congestion evaluation metrics and congestion control strategies. This review reflected state-of-the-art issues and research agenda on congestion control protocols. The merits and demerits of different strategies and protocols were highlighted and discussed in brief. The main objectives of the majority of studies in this field are to extend the lifetime of WSNs and reduce the average end-to-end delay. However, it should not be ignored that many variables and parameters are involved in WSNs; hence, any studies aimed at sorting out and controlling congestion in these networks should consider all these parameters and the interactions among them. As a case in point, the selection of the proper strategy and protocol for controlling congestion should be based on the used applications and the location of the congestion. That is, the congestion location should be regarded as a factor in determining the strategy and protocol. On the whole, congestion control techniques were classified into node level congestion control and link level congestion control. Thus, it can be pointed out that in case of heavy traffic or in persistent congestion conditions, algorithms using resource control are more appropriate than the traffic control mechanism. Moreover, the review of the studies in this domain indicated that, due to uniform energy utilization, resource control-based algorithms can significantly enhance network lifetime. On the other hand, in event-based networks with low traffic, algorithms using traffic control can be more efficient and they have minimum delay. It should be noted that the issues and challenges highlighted in this paper can be controlled and mitigated by congestion control techniques in WSNs which is considered to be a research gap.

The conclusion to be drawn in this extensive survey is that application should be considered as a highly significant and distinguishing factor among various congestion control parameters. Applying the same type of congestion control to all applications and all congestion locations is by no means appropriate and will consequently lead to performance degradation in network. In event-based and query-driven applications, network load is light; hence, these applications can lead to transient congestion occurrence due to short-term burst packet transmission. Thus, it should be maintained that using traffic control techniques can be significantly useful. In continuous applications such as WMSNs, sensor nodes transmit their data continuously to the sink node at a constant rate. Consequently, applying an appropriate resource control scheme can be of considerable significance. Moreover, regarding congestion detection, the consideration of both buffer occupancy and channel load can be effective. Furthermore, since the implicit notification method does not add any extra load to the congested network with respect to congestion notification, it can be of high importance. In congested intermediate nodes, both priority-aware and queue-assisted congestion mitigation schemes can be used to mitigate the congestion.

6.2. Directions for future research

The review of the related literature in this paper helped identify new challenges, problems, open questions and thorny issues on congestion control. This overview paper indicated that there still exist many unresolved issues which should be addressed by interested future researchers. In this paper, the researcher provided a brief overview of major existing congestion control mechanisms for WSNs and compared the advantages and disadvantages of these mechanisms.

In brief, it should be noted that the reviewed schemes in this paper have made significant attempts to tackle the congestion control problems in WSNs from different perspectives and in different circumstances. More research studies on congestion control should be conducted. Future research and works on congestion control schemes in WSNs should focus on the following issues:

(1) Inasmuch as security is regarded as a crucial issue in several applications, an unlawful and erroneous interference might bring about devastating consequences. Thus, the possible interactions between congestion control and security should be the subject of future studies. Moreover, it is essential that researchers develop novel approaches and methods which are aimed at protecting congestion control protocols against malicious nodes or an adversary. Hence, future researchers should zoom in on this security problem and try to sort it out.
(2) Inasmuch as WSNs applications are event-based and unpredictable, future researchers should focus more on self-adapted, distributed, scalable, decentralized and autonomous congestion control protocols.
(3) This review paper revealed that the majority of studies have used simulation as the primary tool for evaluating the proposed mechanisms. Future researchers are recommended to use other novel approaches and techniques of testing and evaluation which are related to real life; that is, interested researchers should apply experimental methods to examine the effectiveness of the proposed schemes. Therefore, the ecological and practical validity of the proposed methods and techniques should be tested in real life scenarios.
(4) Future researchers should devise and design novel techniques such as mobile agent techniques so as to help alleviate congestion control. In other words, researchers should make a trade-off between and among different factors so that not only congestion is controlled and mitigated but also network performance is optimized.
(5) The impact of enhancing multimedia (audio/video) applications for WSNs on congestion control is regarded as a potential direction for further research. Thus, this effect should be taken into consideration in future studies. Emergence of newer WSN generations such as Wireless Multimedia Sensor Networks (WMSNs), Body Area Sensor Networks (BASN), and Underwater Sensor Networks (UWSNs) has framed newer issues and challenges for design and implementation of appropriate congestion control protocols. Energy consumption must be considered in the design of congestion control protocols.
(6) Since the available protocols use either traffic adaptation or traffic flow redirection, hybrid protocol should be developed by future researchers so that both of these techniques can used to adapt traffic rate and redirect traffic at the same time; hence, future researchers can conduct studies and investigate the efficacy of such hybrid protocols on controlling and mitigating congestion in real-life networks. Moreover, cross-layer approach can be used since it is able to interact with different layers such as prioritized MAC, reliable transmission, etc.

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