Congestion control algorithms in wireless sensor networks: Trends and opportunities

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Abstract Congestion control is an extremely important area within wireless sensor networks (WSN), where traffic becomes greater than the aggregated or individual capacity of the underlying channels. Therefore, special considerations are required to develop more sophisticated techniques to avoid, detect, and resolve congestion. The constrained resources of the WSN must be considered while devising such techniques to achieve the maximum throughput. Various approaches have been introduced in the past few years that include routing protocols aided with congestion detection and control mechanism, and dedicated congestion control protocols. In the former schemes, the congestion avoidance is performed by the sink node that causes topology reset and bulk traffic drop. As a consequence, the latter mentioned congestion control protocols addressing the congestion avoidance, detection, and resolution were introduced at the node level. In this paper, we explore mechanisms for controlling congestion in the WSNs and present a comparative study. The congestion control schemes are categorized as centralized with partial congestion control and distributed with dedicated congestion control.

Contents

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0. Introduction

Wireless sensor networks (WSN) (Rekha et al., 2010; Flora et al., 2011) consists of various wireless devices installed with various types of sensors to collect information from the environment. The collected information is relayed from sensor to sensor, using a multi-hop routing protocol towards the desired destination, called sink. At the sink, data aggregation and analysis takes place. The sensor nodes are limited in battery power, memory, and processing capabilities (Flora et al., 2011; Zhang et al., 2012). The aim of various routing schemes is to optimally utilize the resources of WSN to achieve the maximum throughput. Initially, researchers mainly focused on the design of trivial routing schemes to enable data transfer in the WSN. Later on, researchers realized that there must be an efficient mechanism to address the problem when the overall traffic or single link traffic becomes greater than its individual capacity (Rekha et al., 2010; Flora et al., 2011). Such a mechanism is termed as congestion control. Congestion control is of critical importance, as congestion control helps in preventing loss of traffic in bulk. Congestion control is a critical area of research as time variant quantities, such as network traffic and that buffer frequently changes with time (Liu et al., 2012; Wang and Qian, 2011; Tao and Yu, 2010; Ee and Bajcsy, 2004). The priority mechanism must be enforced to ensure the drop of low priority packets in inevitable circumstances. As WSN are resource constrained, a WSN designer must pay attention to the congestion control to achieve maximum lifetime of network by optimally utilizing limited available resources (Rekha et al., 2010; Flora et al., 2011; Lee and Kwangsue, 2010; Sergiou et al., 2007).

Existing congestion control techniques have some limitations, such as (a) optimal estimation of traffic load at congested link, or paths, and along the alternate paths for traffic diversion. (b) The traffic distribution along the alternate paths is not based on the traffic estimation (Tao and Yu, 2010; Ee and Bajcsy, 2004). (c) The priority mechanism is based on hop count rather than actual delay a packet suffers from source to sink (Tao and Yu, 2010; Ee and Bajcsy, 2004; Cheng et al., 2011; Liu et al., 2011). The aforementioned defames the popularity as a practical model. Therefore, more adequate techniques are required to ensure congestion control aided by a sophisticated routing. The details of the previously proposed possible protocols and their comparison along with their in-depth study, working mechanism, and performance metric are discussed in detail in the subsequent sections.

This work is organized as follows. Section 2 presents a brief description of congestion control mechanism proposed in the previous schemes. A pictorial depiction is also detailed to provide an in-depth understanding of the techniques. The qualitative analysis of the schemes with respect to the parameters specified as criteria of each congestion control scheme introduced is also summarized. Existing survey reviews are also elaborated and the shortcomings of the existing survey papers regarding congestion and how this work contributes by overcoming that effectively, is also discussed. Existing protocols are examined thoroughly in Section 3 for standard Quality of Service (QoS) and the performance parameters specified for the congestion control within the WSN. The open issues emerging from our discussion are discussed in Section 4. In Section 5, we conclude our work.

1. Related work

1.1. Existing survey review

Rekha et al. (2010) provided a well-organized work unfolding the exact functionality and techniques employed within the existing literature, and comparative study is performed. The paper presented a graphical illustration that is helpful for the understanding of the readers, particularly where technical functionality is elaborated. The papers reviewed in the survey were balanced in numbers and presented the latest congestion control schemes that enable the reader to get effectively benefited from the complete literature review. Alternatively, Flora et al. (2011) in his survey discussed existing congestion control techniques and incorporated a balanced number of quality citations. Haresh M. Rathod et al. organized their work (Rathod and Buddhadev, 2011) to have an edge by presenting a tabular comparisons of existing congestion control protocols. To summarize, existing surveys found in the literature provides a comprehensive review of old congestion control schemes, Therefore, there is a need for a comprehensive survey that provides a detailed review of old as well as latest congestion control schemes, provides taxonomy, and identifies open research issues. With these issues in mind, we write this survey.

1.2. Congestion control schemes

Congestion control schemes found in the literature can be divided into two main categories namely: (a) Centralized Congestion Control Schemes containing routing protocols
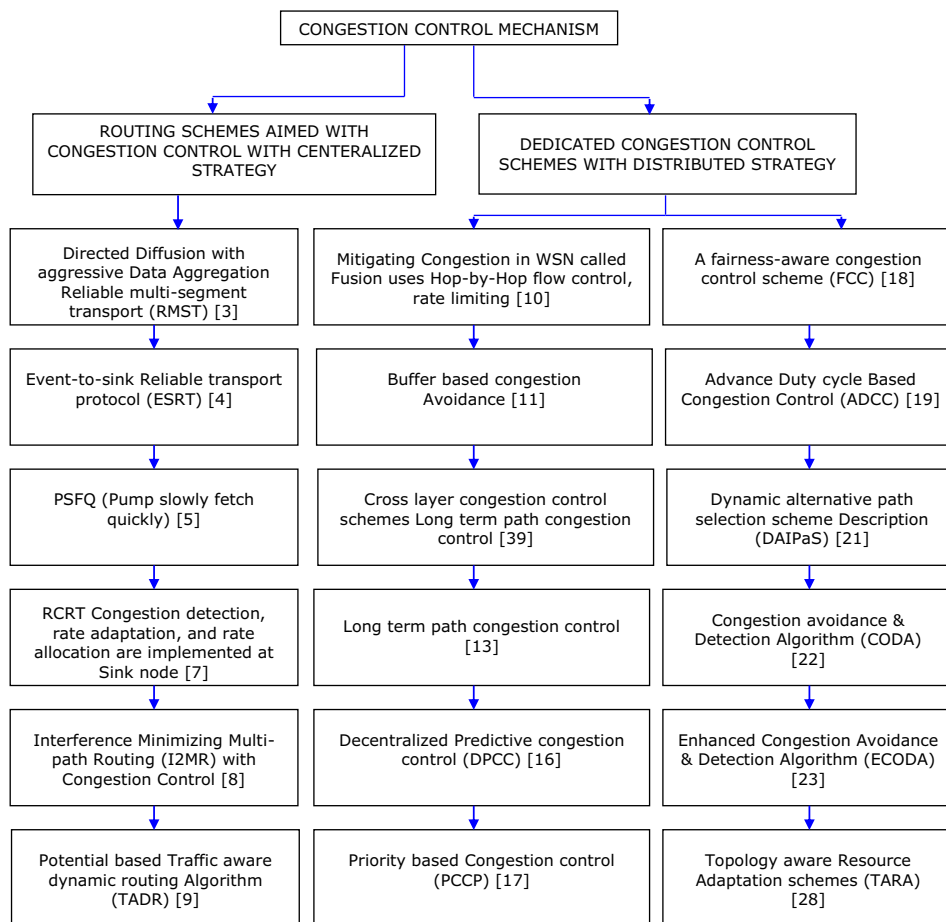
Fig. 1 Evolution and categories of congestion control protocols.

aided with congestion control and (b) Distributed Congestion Control Schemes contains buffer based and cross layer congestion control schemes. Fig. 1 presents a detailed taxonomy of existing congestion controlled schemes.

1.2.1. Centralized congestion control schemes

In the centralized congestion control schemes, all the actions related to avoid or control congestion are undertaken by the sink node/base station. Here, all the activities related to the congestion control, such as congestion detection and congestion avoidance are taken by the sink. Sensor nodes merely serve as a "dump entity" that takes decision by the commands dictated by the underlying congestion control scheme at the centralized sink. In a typical centralized congestion control scheme, the sink, periodically collects data from the sensor node, detects the possibility of congestion, and accordingly sends messages to the involved sensor to overcome congestion. A qualitative analysis of the distributed congestion control schemes is summarized in Table 1. The following is a detailed discussion on some of the important centralized congestion control schemes found in the literature.

Intanagonwiwat and Estrin (2000) proposed Directed Diffusion as an application aware routing protocol. This protocol generates a query from the sink that is broadcast to the sensor nodes. The sensor nodes determine nature of the query, and reply to the intermediate sensors to form a gradient path

to the sink. The sink selects the paths, the source sensor transmits the data, and the sink avoids the congestion by aggregating the data. The gradient direction determines the flow along the shortest paths to the sink. The congestion is avoided, as the sink selects the single path for the data transmission. The operational scenario is depicted in Fig. 2. Sankara et al. proposed ESRT (Sankaras and Akyildiz, 2003), a transport protocol that supports congestion resolution. The sink node detects congestion by monitoring the sensor nodes local buffer. The sensor node sets the congestion notification (CN) bit in the header of the data packets for the sink. The sink on receiving the packet, determines the congestion and a new network state, such as No Congestion and Low Reliability (NC, LR), No Congestion and High Reliability (NC, HR), Congestion High Reliability (C, HR), and Congestion Low Reliability (C, LR), repeatedly. Based on the decisions by the sink, using these network states, the optimal operating region is formed by specifying a radius for event sensing. The event is detected within the radius and is routed to the sink in the form of data. The entire procedure is explained in Fig. 3.

Wan et al. proposed PSFQ (Wan et al., 2002) to determine, prevent, and resolve the congestion by modulating its pump/fetch ratio. Data from a source are distributed with relatively slow speed (pump slowly). In case of data loss at a particular node, node recovers the same data segment by fetching quickly (local recovery). However, in case of packet loss, a negative ACK is sent to the sink/source node. Both Directed Diffusion

Table 1 Comparison of the existing centralized routing protocols with the congestion control.

| S.No	Protocol	Operational strategy	Congestion detection criteria	Priority criteria	Packet drop priority	MAC
01	Directed diffusion	Routing with aggregation, distributed in nature	Buffer overflow	No	No	CSMA
02	ESRT	Routing with congestion support, Centralized in nature	Buffer overflow	No	No	CSMA
03	PSFQ	Routing with congestion support, Centralized in nature	Buffer overflow	No	No	CSMA
04	RCRT	Centralized congestion detection, rate adaptation, and rate allocation	Buffer overflow	No	No	CSMA
05	I2MR	Routing aided by congestion control	Buffer Occupancy, and, exponential weighted moving averages for long term congestion detection	No	No	No
06	TADR	Routing with congestion control	Buffer and Rate, hybrid scalar potential field	No	No	NA
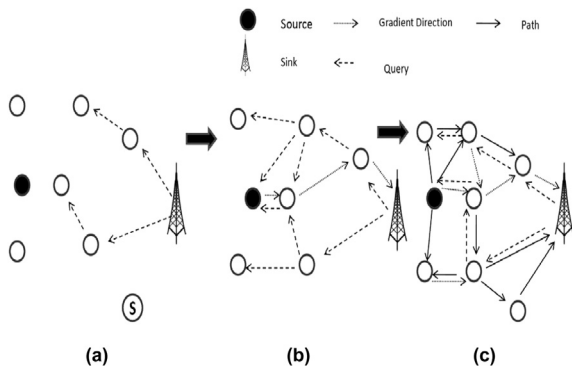
Fig. 2 Directed diffusion, (a) sink broadcast query, (b) Gradient formation for reply. (c) Flow of reply toward sink along the gradient (Intanagonwiwat and Estrin, 2000).
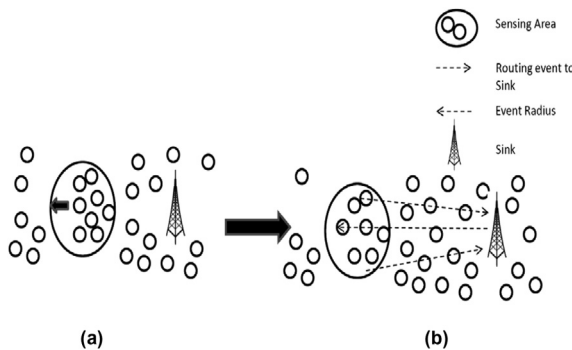

Fig. 3 (a) ESTR event radius, (b) Data sensing across event radius and transmitting to sink (Sankaras and Akyildiz, 2003).

and PSFQ can avoid congestion but both require the technical details, such as sensed channel load and fixed channel state sampling as specialized parameters along with accurate time configurations. The administrator at the sink is required to be aware of the specialized parameters. The effectiveness of

these techniques is more based on specific scenarios rather than a generic solution for the WSN.

The RCRT proposed by Paek and Govindan (2004) is a transport protocol that resolves the congestion by determining and allocating data rate. The congestion detection, rate control, and allocation take place at the sink. The main drawback of this scheme is the slow convergence rate and the inability to distinguish flow constrained in bottleneck regions. The operational mechanism of RCRT is depicted in Fig. 4. Teo et al. (2008a) proposed the I2MR routing protocol aided with the congestion control mechanism. The I2MR protocol reserves multiple alternate paths for routing data to eliminate congestion. The protocol detects the long-term congestion by observing single buffer of source node using the exponential weighted moving averages. To control congestion, the protocol notifies the source node for reducing the transmission rate. The source node reduces the transmission rate by diverting the traffic to the alternate paths, by selecting the path among the multiple alternate paths that can accommodate the maximum traffic. The I2MR protocol has its limitations when the alternate paths are unavailable or cannot accommodate the traffic rate specified by the source node. In such circumstances, a huge data loss is inevitable. The rate adjustment is based on the predefined rules that are 1/4, 1/6 or 1/8 of the link data rate rather than on the estimated traffic that results in inefficient channel
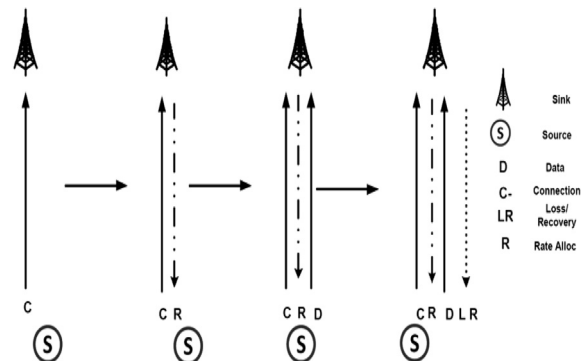

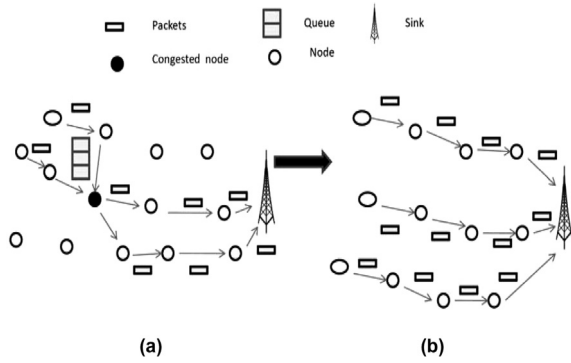**Fig. 4** RCRT setup phase (Paek and Govindan, 2004).

Fig. 5 TADR operations, (a) Traffic monitoring, (b) traffic diversion (Ren et al., 2011).

utilization. Similarly, the transient congestion remains unaddressed, despite many to one nature of the WSN.

The TADR (Ren et al., 2011) protocol by Fengyuan et al. defines a hybrid scalar potential field comprising of depth and queue length field. The former provides the backbone for routing the packets to the sink along the shortest available paths, while the latter makes the TADR traffic aware. In case of congestion, the packets are forwarded to the alternate paths that consist of idle or under- loaded nodes. A bypassing hot-spot rule is introduced to avoid hot spots. However, the limitation is to understand the time variant potential fields that lead to the experimental values rather than the optimal values. The aforementioned is further detailed in Fig. 5.

1.2.2. Distributed congestion control schemes

This category includes the congestion control schemes that are distributed in nature. The congestion control mechanism spans over the entire sensor field. The sparse deployment nature of sensor nodes results in the distribution of congestion control algorithm into various routines and sub routines across the WSN. These routines are executed by certain events in the sensor fields called stimulus and accordingly produce response. The output of one routine/subroutine may act as a stimulus to another subroutine. A qualitative analysis of the distributed congestion control schemes is summarized in Table 2. The congestion detection criterion is elaborated with the operational strategy, the packet priority and the medium access control mechanism.

Hull et al. (2004) proposed Mitigating congestion that employed three techniques namely: (a) hop-by-hop flow control, (b) rate limiting, and (c) prioritized MAC. These schemes are collectively referred to as fusion and they prevent nodes from transmitting their packets when they are destined to drop. The hop-by-hop flow determines packet drop when there is an insufficient space in the output buffer of downstream nodes. Rate limiting ensures fairness in network transmission, especially from the nodes farther from the sink. Prioritized MAC is responsible for ensuring prioritized access to the channels for congested nodes. The technique proposed in Hull et al. (2004) does not rely on the topological information, rather, focuses on the single-sink and the spanning-tree topologies. The trade-off between the channel utilization and fairness is also considered. The challenging issues like interference between apparently disjoint set of nodes, and inherently lossy nature of wireless channel are addressed appropriately.

Table 2 Mutual Comparison of existing distributed congestion control protocols.

| S.No	Protocol	Operational strategy	Congestion detection criteria	Priority criteria	Packet drop priority	MAC
01	CODA	Congestion control	Single buffer occupancy and, link loading conditions	NO	NO	CSMA (VC)
02	ECODA	Congestion control	Dual buffer occupancy	Yes	Yes	CSMA with AIMD
03	FCC	Congestion control	Buffer occupancy, incoming flows	Probabilistic algorithm	No Priority, probabilistic algorithm	Application based, rate control
04	DAIPaS	Congestion control	Buffer occupancy, channel interference	NO	NO	NA
05	ADCC	Congestion control	Buffer occupancy, and, link load	NO	NO	802.11
06	LPCC	Congestion control	Transient buffer monitoring using EWMA	NO	NO	NA
07	PCCP	Congestion control	Buffer monitoring, packet inter arrival time, and, service reflecting congestion	NO	NO	NA
08	DPCC	Congestion control	Buffer occupancy and traffic flow	NO	NO	CSMA, Back off interval
09	LACAS	Congestion control	Learning automata	Pre defined rules	Pre defined rules	NA
10	Fusion	Flow control, rate limiting, and prioritized MAC	Buffer and rate	NA	NA	CSMA with RTS/CTS
11	Buffer based congestion avoidance	Congestion control	Buffer occupancy	NA	NA	CSMA with implicit ACKs and TDMA with fix scheduling
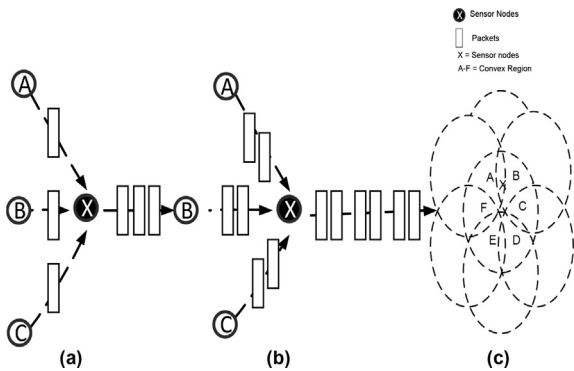
Fig. 6 Buffer based congestion avoidance scheme employing (a) CDMA, (b) TDMA and (c) $1/k$ buffer solution (Chen and Yang, 2006).
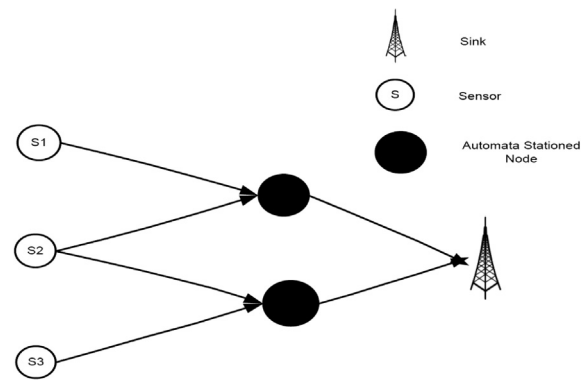

Fig. 7 LACAS operational scenario (Misra et al., 2009).

However, the technique proposed (Hull et al., 2004) utilizes CTS/RTS mechanism to avoid hidden terminal problem like CODA (Tao and Yu, 2010) and increases the control over-heads as network grows. To avoid queue overlap, the application adaptation is adjusted to wait until queue accommodates more data. However, in this scheme data priority remains silent that needs to be addressed.

Buffer based congestion avoidance scheme introduced by Chen and Yang (2006) is tested against various MAC protocols, such as CSMA with implicit ACKs and TDMA with fix scheduling, as explained in Fig. 6. The hidden terminal problem was addressed with a 1/k buffer solution. The fairness for buffer access and load balancing over multiple paths is assured in this scheme. The scenario is explained in the Fig. 6(c). Sudip et al. proposed LACAS (Misra et al., 2009) scheme based on the learning and adaptive automata. The LACAS protocol either responds to a predefined set of rules or adapts to a new situation and updates its adaptive automata by learning to address the many to one nature of the WSN. The learning automaton (LA) consists of finite sets of states that respond to a favorable or unfavorable environmental behavior, depending on the predefined probability. The uncertain nature makes the LA favorable for the aforementioned type of the network. The automatons are stationed at the intermediate nodes, called the Automata Stationed Nodes (ASN) and control the behavior of the nodes. ASN takes input from a predefined set, against that the random output is generated. The correctness of output depends on the probability factor. The probability factor updating process will move on till a favorable action is determined. The entire scenario is depicted in Fig. 7. Mehm et al. for a local cross layer congestion control scheme (Mehmet and Akyildiz, 2010) proposed the congestion detection by considering the buffer occupancy. The role of buffer is twofold: (a).holds sensed data and (b) accommodates relay packets/traffic. Each node is responsible for transmitting and routing traffic using its neighboring nodes. A node also controls congestion by adjusting the sensing and routing rate. Long-term path congestion control determines congestion along active path comprising the intermediate nodes. This notifies the source to reduce loading rate. The source settles the highest rate incompliance with the active path capacity. The intermediate nodes detect long term congestion using exponential weighted average by monitoring their transmit

buffer and sends the congested packet to the source to ensure reduction of the loading rate.

Maciej et al. proposed DPCC (Zawodniok and Jagannathan, 2007) that uses rate control adjustment, back-off interval selection, and distributed power policy for congestion control at each of the WSN nodes. The DPCC considers buffer occupancy at each node for congestion detection. Once congestion is detected, the backpressure message is generated to diminish congestion on the basis of hop-by-hop estimation of traffic flow. The priority based congestion control by Wang et al. (2007) introduced the concept of node priority index. The scheme is upstream in nature and is designed for many to one communication. The scheme is based on Intelligent Congestion Detection (ICD). The ICD detects congestion based on packet inter-arrival time and service reflecting congestion level along with detailed information. The Implicit Congestion Notification (ICN) is responsible for piggybacked congestion information in the headers to avoid control flow overhead. The priority based rate adjustment (PRA) indexes the nodes based on priority. The index value determines the bandwidth allocated to each node.

Kang et al. proposed TARA (Kang et al., 2007) that utilizes the redundant resources of the sensor field. The TARA activates sensor nodes in sleep state to extend the existing topology. The congestion is detected at the hot spots by comparing congestion level with certain water mark. The TARA protocol utilizes distributor nodes and merger nodes to serve distributing the traffic from the source path to the alternate/detour paths, and merge the flows, respectively.

The FCC (Xiaoyan et al., 2009) protocol by Xiaoyan et al. restricts the sending flow of each sensor at the earliest. The FCC protocol aims to drop the packets near the source node to avoid unnecessary energy consumption, as packets are likely to be dropped near the sink. The nodes near the source maintain per flow state, and allocate approximately fair rate by comparing incoming flow and shared bandwidth. The nodes near the sink use probabilistic algorithm for the packet drop based on buffer occupancy. On the packet drop, the node near the sink sends a warning message (WM) to the near source nodes that calculate and adjust the flow rate by sending the CM message as depicted in Fig. 8. This scheme adopts traffic restriction strategy rather than accommodating flows for re-route mechanism. The priority for packet drop is not considered in this scheme.
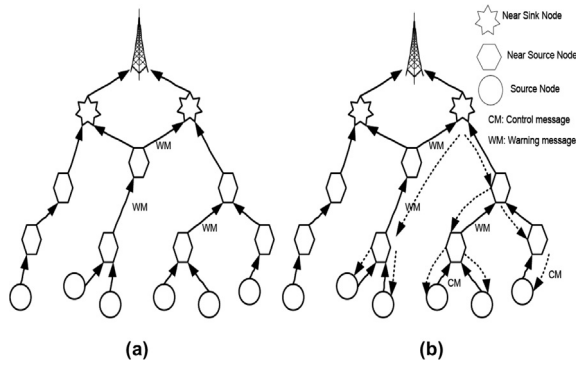
Fig. 8 FCC congestion control (a) WM broadcast by near sink node on packet drop, (b) CM generated by near source node after rate adjustment (Xiaoyan et al., 2009).

The ADCC (Lee and Kwangsue, 2010) protocol proposed by Dongho et al. is a congestion control scheme for the WSN based home automation and is equally useful to general sensor network based on the duty cycle adjustment of the sensor devices. The ADCC protocol controls the congestion based on resource control scheme, and traffic control scheme. The ADCC protocol periodically calculates the service time by monitoring the incoming packets at MAC level to identify congestion. When congestion degree lies below the certain threshold, the duty cycle is adjusted to reduce the congestion. If traffic is raised above the specified threshold, then the sending rate of the resource is reduced. The detailed operation of the ADCC protocol is shown in Fig. 9. The ADCC protocol considers the buffer occupancy and the link load to detect congestion. However, the single buffer occupancy is insufficient to estimate the right level of the congestion and is used for the home based automation. Charalambos et al. proposed the DAlPaS (Charalambos and Vasosu, 2011) protocol that is a dynamic distributed congestion control protocol. The DAIPS protocol takes into account the buffer occupancy, channel interference, and individual node energy to detect congestion. The protocol dynamically selects the shortest path and routes the traffic to avoid/resolve the congested node/link. The DAlPaS protocol starts with the initial setup phase, where the topmost nodes sets the level ID to 0 and broadcasts a "hello" message to all the nodes within the active range. Upon receiving the "hello" message, each node increments the ID value by 1 and broadcast the message. This process continues
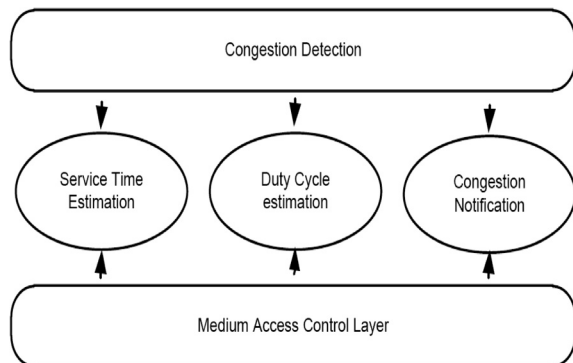

Fig. 9 ADCC congestion control (Lee and Kwangsue, 2010).

until all the nodes receive a unique level ID. Each node is assigned a unique ID based on its level. Each node maintains an ID to manipulate shortest path or to find alternate paths to the sink. The flow from the higher value to the lowest value will determine the shortest path to the sink. Using the buffer occupancy, comparison between incoming flow, and the transmission flow determines the congestion. The DAlPaS protocol enters into the soft stage where the receiving node sets "Next Packet Sequence Number" to "false" in the ACK packet header and sends the packet to the forwarding node.

On receiving the value, the sending node receives the message to select the alternate paths. The sending node will continue to send data along the same path or to a new destination. However, if buffer occupancy exceeds the minimum threshold or the incoming flow becomes greater than the transmission rate, the DAlPaS protocol enters into a hard phase and diverts the flow to move along the new path. The DAlPaS protocol readjusts the topology by removing the node from the active path.

Wan et al. proposed the CODA (Tao and Yu, 2010) protocol that consists of three main phases. Congestion detection is based on the current single buffer occupancy, combination of link, past, and present channel loading conditions. The protocol adopts the sampling scheme at an appropriate time interval for the local channel monitoring thus preserving energy. Upon detecting congestion, each node broadcasts hop-by-hop, the backpressure message, which propagates to the source directly or travels upstream towards the source. Depending on the local network conditions, the message is further propagated. In a close loop regulation, upon successful receipt of the ACKs, the source maintains its rate. Due to the loss of the ACKs, the source adjusts its rate accordingly. The CODA protocol utilizes CSMA for medium access control and utilizes virtual career sense to avoid hidden terminal problem that is not energy efficient scheme, as RTS and CTS are frequently exchanged to avoid the collision that results in extra consumption of the energy.

Tao et al. proposed the ECODA (Ee and Bajcsy, 2004) protocol that adopted a more realistic approach for congestion detection. The protocol incorporates dual buffer and weighted difference for detecting congestion. For transient congestion, unlike others, the ECODA protocol deals with three buffer states, namely: (a) Accept State, (b) Reject State, and (c) Filter State. The protocol deals with each state separately to avoid or resolve congestion. Flexible priority schemes have been adopted for the static and the dynamic priority. The protocol helps to forward the high priority data or drop of the low priority packets. However, the ECODA protocol cannot avoid the higher priority data overwritten by lower priority packets due to queue model used. Similarly, priority mechanism does not consider the actual delay a packet has to come across during transmission. The hop count is a multiplicative entity in numerator as evident in the Eq. (1).

$$Dynamic\_priority = \alpha \times hop\ count$$
$$+\ static\ priority\ (Packet)/1 + \alpha$$
$$\times\ Delay, \quad\quad (1)$$

where α and β are network dependent parameters. The separation of the sensing buffer from the transmission buffer makes the scheme more appropriate for forwarding the high priority packets.

Meera S. B.Tech et al. proposed Congestion Control in wireless sensor networks using Prioritized Interface Queue (Meera et al., 2012) introduced dual queue to control congestion using cross layer approach. An intermediate node implies congestion control mechanism to improve the network performance by reducing the data forwarding rate to the downstream nodes. The intelligent routing selects the best node having low traffic to forward the packets. The intelligent routing is performed using congestion information provided by the sink. The flexible queue is introduced at the interface of network and MAC layer is introduced where node generated traffic. The incoming traffic is separately placed in the dual queues. The separate threshold is specified for both the queues. When threshold arises, the data from the packets queue are overwritten by the incoming traffic as packet drop penalty is higher than the drop penalty. However this strategy may results in loss of target data in a situation where recently sense data contain the target data, which will be overwritten by the incoming data. In order to control transient congestion when transient buffer reaches to the threshold value it reduces the sending rate to the downstream nodes.

Michopoulos et al. proposed nicely categorized congestion detection and avoidance (Michopoulos et al., 2011) based on the study of the previous schemes. The congestion detection (CD) is categorized as (1) buffer state monitoring (2) Intelligent collision detection by monitoring the channel occupancy. The former is further categorized as buffer threshold; when buffer reaches certain static/dynamic threshold value and periodic buffer; that detects congestion by periodically checking the buffer capacity. Whereas collision avoidance (CA) is normally based on adjusting the rate locally when a node is congested its child nodes are forced to adjust their rates mostly employing additive increase and multiplicative decrease (AIMD).Based on their experiments they have concluded that the congestion detection based on packet service time/ packet arrival time performed poorly in IPv6 over Low power Wireless Personal Area Networks (6LoWPAN).

Zilong Li et al. introduced a cross layer congestion control scheme (Li et al., 2011), the multiple paths from source to sink are established first and then cross layers information is shared in the form of state frame. This frame is transmitted upward to update and share the congestion information of the node. The upstream nodes keep and update the congestion information pertaining to the Buffer Occupancy (BO) for many downstream nodes. Hence routing is done based on this information. The congestion degree of any node is calculated by using the formula $C = \frac{k(1-BO)}{n^2}$, Where k and n are adjustment factors.

Vasilis et al. introduced buffer based new approach for congestion control (Michopoulos et al., 2010). Their scheme ensures fairness by allocating equal bandwidth for all the sensor nudes. According to this strategy the buffer is adjusted according to the transmitting rate of downstream nodes in order to avoid packet drop. The transmission rate of a node is adjusted to recover from congestion with minimal loss of data. The congestion detection is based on the information a node reserves proactively for downstream nodes. The rate is adjusted by the formula $r_k = r_i \times \frac{SUM_k}{SUM_1}$, Where SUM_1 is the number of source traffic, SUM_k represents the number of traffic of neighbors of node i, r_i is the transmission rate of node i and r_k is the transmission rate of the node k which is being adjusted.

Junjie et al. (2012) summarize nicely the concept of LIFO and multi-queue-LIFO, the simulation results and comparisons shows that it provides better performance over traditional FIFO queue mechanism and also ensures the improved fairness and delay for the congested WSN.

2. Congestion control in IEEE 802.15.4

An emerging standard called IEEE 802.15.4 specifically designed for Personal Area Network and wireless sensor network's devices (WSN) having low transmission rate. Guranteed Time Slot (GTS) medium control mechanism enables it to support time sensitive WSN. It uses career sense multiple access to avoid congestion at MAC level using CSMA/CA. It utilize Binary exponential backoff (BEB) mechanism to share the channel among the wireless devices at low rate, low cost and low power. However it degrades the performance in an environment with a large sensor field having too many devices with large collision probability. This short coming is due to its small range of backoff exponent which is not based on actual state of underlying channel rather it use deterministic approach.

3. Design goals

The following is a list of design goals for congestion control schemes. The most important design goals for congestion control schemes includes fast response, high transmission reliability, fault tolerance, interoperability, wear-ability, low-power consumption, inexpensiveness, and complexity of the WSN. Directed diffusion aided with RSMT (Intanagonwiwat and Estrin, 2000) takes advantage of the shortest path to improve reliability and efficiency. Reliability is a prime objective of congestion control in Mitigate Congestion in WSN (Hull et al., 2004). The link layer is implemented semi-reliably with a maximum retransmission count, while congestion control at MAC layer remains unaddressed. The RCRT (Paek and Govindan, 2004) protocol being a reliable transport protocol incorporates end-to-end explicit loss recovery at the sink and ensures better aggregated control of traffic and flexible rate allocation criteria to achieve reliability. However, unlike the TADR (Teo et al., 2008a) protocol and the Multi-path Load Balancing in the Multi-hop, reliability remains unaddressed (Ren et al., 2011). Fault tolerance is not emphasized in either of aforementioned schemes. The LACAS (Misra et al., 2009) protocol controls the packets rate flow. Therefore, the protocol aids in conserving energy, ensuring fair, and reliable transmission across the network. However, fault tolerance still remains a salient feature. The I2MR (Ren et al., 2011) protocol employs the 802.11 Distributed Coordinated Function at the MAC level. The protocol incorporates exponential back off along the physical career sensing. The retransmission maximum limit is set to two attempts for two way Data-ACK handshaking. To avoid congestion and control overheads CTS/RTS control packets are turned off and the MAC headers are kept unfragmented.

The ECODA (Ee and Bajcsy, 2004) protocol outperforms the CODA (Tao and Yu, 2010) protocol in terms of efficiency, as the latter sends the rate adjustments dependent on the feedback from the sink. In the case of persistent congestion, the consumption of extra energy or the loss of the ACKs takes

place due to either congestion or link variation. The former overcomes such a problem by adopting a source control scheme at bottleneck node without consuming extra energy in a robust manner. However, the CODA protocol is unable to deal with the congestion when several buffers reach the threshold, simultaneously.

The CODA (Tao and Yu, 2010) protocol, on the other hand, introduces a new stream. The reliability and congestion control needs to be separated to achieve adequate design of sensor network protocols. The Virtual Circuits (VC) and link Automatic Repeat Request (ARQ) at data link layer are essential for the critical information exchange, but do not have the same worth in controlling the congestion. Therefore, the CODA protocol design does not consider packet/data loss, and does not ensure recovery. The CODA protocol eventually decouples the reliability and other control mechanism, that enable the CODA protocol to work with or without the reliability support. To utilize the CODA protocol with or without reliability, depends on the type of application providing flexibility for different type of applications The QoS and other important aspects for design goals of Congestion Control Protocols are summarized in the Table 3.

4. Open issues

In this paper, we reviewed the existing congestion control protocols and provided a taxonomy based on the distinct features. In each class of the devised taxonomy, popular congestion protocols were discussed in detail. The comparative analysis of prominent features of various congestion control schemes are summarized in Table 1 and Table 2. Based on the rigorous literature review, we have identified some open research issues in the existing congestion control protocols, enumerated below.

4.1. Traffic estimation

Network traffic estimation at congested nodes and along the available alternative paths is essential. Consequently, clear statistics for traffic accommodation or dropped packets must be obtained. The estimation can be further used to either divert the traffic or drop packets along the alternative paths. Strategies, such as additive increase and multiplicative decrease are not fast enough to resolve congestion, eventually resulting in the frequent data/packet loss.

4.2. Traffic diversion is lacking coordination with rate control/adjustment

Traffic diversion to avoid the congestion is lacking coordination with the rate control/adjustment and the estimation. Traffic diversion to avoid congestion must take into account traffic estimations at the congested node(s) and along alternate paths. The dedicated forwarding node leads to the dense deployment that eventually leads to interference causing congestion.

4.3. To ensure low priority packet drop

The priority packet drop mechanism is based on the hop count rather than the actual delay. Therefore, packets generated from the root/bottom, always enjoy a higher priority. A hybrid approach can be used in that the alternate drop of the packets at each node from the sensing buffer and the intermediate buffer. Such a methodology will avoid a bias for one type of packet priority drop. Moreover, there is no mechanism to avoid the drop of higher priority packets from the tail of the queue. All the previously proposed protocols have used same queuing model.

The mechanism that acts as a stimuli for the traffic diversion must be enhanced in way that it promptly gathers statistics for congestion well ahead so that congestion in term of packets can be determined, there may be a the same mechanism along the alternate/available path that determines how much packets can be accommodated for traffic diversion along the each alternate path. There may be an effective statistics sharing among these two components so that traffic in term of packets is adjusted according to the capacity of the number of packets along the alternate paths, this will reduce the number of packet loss considerably.

The direction/mechanism to solve the open issues can be followed be as possible/potential research direction either by incorporation new or modifying existing queueing mechanism in existing congestion control scheme. Queueing model adaption positively help to drop low priority packets thus ensuring packet drop must not drop target data. The algorithm that drops packets can also be enhanced to efficiently/effectively utilizing the queueing model also with the incorporation of some experimented based new packet drop mechanism. The packet drop must not be enforced from the single buffer rather a random packet drop may also be applied.

Table 3 Summary quality of service (QoS).

S.No	Protocol	QoS			Location aware
		Fairness	Stability	Fault-tolerant	
1	ECODA	✔	×	×	×
2	CODA	×	×	×	×
3	Congestion avoidance based on lightweight buffer	×	×	×	×
4	A fairness-aware congestion control	✔	✔	×	×
5	ADCC	×	×	×	×
6	DAlPaS	×	×	×	×
7	12MR	×	×	×	✔ (Assumption)
8	LACAS	×	×	×	×
9	Mitigating Congestion	✔	×	×	× (Future-Aspect)
10	Multipath Load Balancing in Multi-hop	×	×	×	×
11	TADR	×	×	×	×

5. Conclusions

Congestion control in WSN is a challenging area. Resource limitation makes the task of devising techniques to control congestion more challenging and complex. This work presented a comprehensive review on the existing techniques. All the techniques aimed to control congestion as a common task to extend the network life time by effectively utilizing the limited available resources. These techniques were classified into the centralized and the distributed strategies based on their primary and secondary design goals. Each technique was thoroughly discussed and evaluated using different performance and design metrics used for measuring the congestion. We found that the existing techniques were effectively striving to control congestion. However, the areas within the congestion control that required more sophisticated mechanisms were elaborated as open issues for future research.

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