A Capacity Aware Data Transport Protocol for Wireless Sensor Network

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Abstract. Wireless link capacity within a sensor network has direct impact on its performance and throughput. Due to dense sensor deployment, interference seems to be a key factor for varying radio link capacity and also for congestion at hot spot region. Thus it is important to handle interference while removing in-network hot spots. The main goal of this paper is to achieve maximum utilization of link capacity for each sensor node controlling congestion related packet losses. Therefore in this paper we proposed an interference and capacity aware data transport protocol for sensor networks which performs rate control over congested wireless links. Proposed approach[1] identifies the congested links that exists in hot spots and then adapts data transmission rate of corresponding sensor nodes. Perception of radio link interferences i.e. intra-path and inter-path interferences are used to estimate the capacity of each link. Finally simulation outputs have demonstrated the effectiveness of the proposed task and showed a noticeable performance in terms of packet delivery ratio, packet delivery latency and sensor's runtime buffer size.

Keywords: Link Capacity, Interference, Data Transport, Congestion, Rate Control.

1 Introduction

Due to shared nature of the wireless medium all sensor nodes in a dense sensor network contends for medium access and observes variation for link capacity. Therefore congestion usually occurs in the hot spot regions and overall network performance and throughput reduce as well. Due to dense sensor deployment, interference seems to be a key factor for varying link capacity and hot spot congestion. In wireless communication, radio interferences comprises both inter-path interference and intra-path interference [1]. Interference causes severe network

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performance degradation and reduces channel capacity utilization. Therefore solutions are required to control the congesttion at hot spot region.

In a multi-hop and multi-path communication model of sensor networks, intermediate sensor nodes and their corresponding wireless links carry disproportionately large amount of traffic. There will be obvious loss of data packets at intermediate nodes if they can not get sufficient channel access to transmit their data. It also causes delay which radically consumes huge amount of energy. In a dense sensor network with CSMA MAC [2] protocol, contention could carry out over long time turning out to be the same effect for intermediate nodes and finally service rate of sensor nodes bound to decrease.

In this paper, we proposed a link interference and capacity aware data transport protocol for sensor networks which performs rate control over congested wireless links. An efficient congestion detection mechanism presented in this paper considering varying link capacity and multiple flows passing through the network. Proposed approach identifies the hot spot congestion that exists in the network and then controls the data transmission rates of corresponding nodes of the congested links. This data transport scheme performs rate control considering both link interference and node buffer occupancy. The main goal of this paper is to achieve maximum utilization of link capacity for each node reducing packet losses due to congestion at intermediate nodes. Proposed technique seems to be an efficient one to identify congestion at in-network hot spots and able to reduced packet losses due to congestion.

The rest of this paper is organized as follows: section 2 presents several background studies on congestion control and avoidance techniques for sensor networks. Subsequently section 3 describes our protocol assumptions and sensor network model. Section 4 represents the capacity estimation model and in section 5 the proposed capacity aware data transport scheme is discussed in detail. Section 6 has gone through experimental results with simulation efforts and explanation. Finally section 7 concludes this paper with the contributed features of this paper.

2 Related Work

In this section, citation done on background studies on various aspects of previous rate adaptation mechanisms, their effects and techniques. Previous congestion control and avoidance techniques for sensor networks can be categorized based on the awareness of wireless link interference and link capacity.

In case of sensor networks the very early interference aware rate control approach is IFRC [3]. It is a distributed rate allocation scheme where each sensor nodes share the congestion of other nodes through overhearing. It congregates to allocate an optimal and efficient rate for each of the sensor nodes. QCRA [4] is an infrequent rate allocation scheme, where sink node is responsible to assign individual rate for each sensor nodes. Parameters consider in this solution are topology information, routing information and link loss rate information. A very recent work Flush [1] implemented a novel pipelining mechanism for dynamic rate control for sensor network considering intra-path interference. It is a reliable protocol that provides end-to-end reliability, but assumes that different flows do not interfere with each other. TARA [10] employs a capacity increasing resource control approach during the period of congestion. They proposed a very effective capacity analysis model handling interference with the aid of graph colouring technique. In TARA number of control packets exchange required during the congestion state of a network and which might create a huge overhead for sensor networks.

Besides all these rate adaptation schemes, there are a good number of contributed works for congestion control in sensor networks. Among them ESRT [5] is one of the earliest work for centralized congestion control. It is a sink initiated rate control protocol for event driven applications and in this approach all nodes in the network are considered to be within one hop away from the sink. CODA (Congestion Detection and Avoidance) [6] is another rate control protocol for the upstream sensor nodes. In this approach, each of the nodes in the network controls their rate using AIMD fashion. Fusion [7] can be found as an efficient congestion control mechanism. It studies three approaches namely: hop-by-by flow control, source limiting scheme and prioritized MAC; operates at different layers of the traditional protocol stack. Finally, RCRT [11] proposes a reliable rate control protocol for loss-intolerant applications. It is a centralized sink initiated transport protocol that ensures efficiency and flexibility. Wireless link's load and capacity seems to be the key factor for the purpose of rate control.

It is to mention that among all these protocols, many protocols addressed interference issue for data transport in sensor network. None of them except Flush [1] handled intra-path interference for rate control. Flush [1] is a protocol to be work in a single path or chain topology and it does not consider inter-path interference. Therefore, we inspired to design an efficient data transport protocol for sensor network considering both types of interference namely inter-path and intra-path interference.

3 Network Model and Assumptions

Proposed data transport protocol particularly depends on channel capacity and link interferences. The basic goal is to identify in-network hot spot regions and congested links through capacity estimation. Then our scheme perform rate control on the corresponding sensor nodes so that congestion can be removed and packet drop ratio can be reduced.

3.1 Network Model

In a multi-hop wireless network inter-path interference are likely to happen while at the same time wireless links of different paths interfere with each other. Again intra-path interference [1] occurs within a single path between different wireless links, where transmission cannot take place on a link due to the interference from its up and downstream links. According to the CSMA MAC [2] protocol,

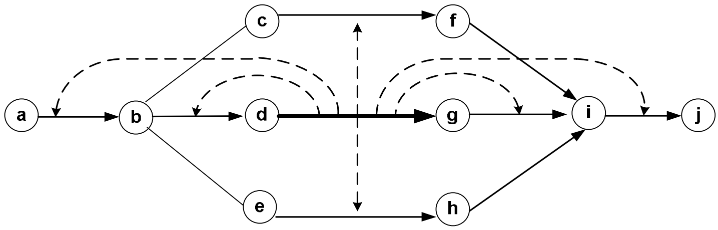

Fig. 1. Inter and Intra Path Interference Scenario

wireless links sharing a common channel; among them only one link is permitted to transmit at any given time and it is due to inter and intra path interferences.

In Figure 1 link (d, g) is forwarding the traffic of source node a to the destination node j at a given time. Due to this ongoing transmission on wireless link (d, g) inter-path interference restricts links (c, f) and (e, h) from forwarding any traffic. Same data forwarding on link (d, g) also restricting it's interfering links (a, b), (b, d), (g, i) and (i, j) on the same path from node a to j due to intra-path interference.

Depending on the general architecture of sensor network model, all subsequent discussions are based on the CSMA MAC [2] protocol standard. In routing layer, both single path and multipath routing protocols can be considered with pre-established paths from source nodes to the sink node. Sensor nodes are battery operated with limited power and they are stationary. Network operation time has been divided into equal time epochs (duration) having duration t. It is assumed that each sensor node piggybacks its data transport information (i.e. current trasmission rate, current transmission interval, and runtime buffer size) on each transmitted data packet so that all of its neighbors can aware of these parameters through overhearing.

3.2 Definitions

The following definitions work as the basic assumptions of the proposed data transport protocol.

Definition 1: Consider a sensor network $G(N, L)$, where a set of active links $l_{(i,j)} \subseteq L$ transmits data at each epoch t. In case of a link $l_{(i,j)} \subseteq L$, each transmission sets off from node i (sender) to node j (receiver). Link $l_{(i,j)}$ said to be active when node i is backlogged.

Definition 2: The interference set, $inf_{l_{(i,j)}}$ includes all the active wireless links which interferes with link $l_{(i,j)}$. Interference set, $inf_{l_{(i,j)}}$ comprise with wireless links whose atleast one endpoint (sender or receiver) is at interference range of either i or j or both (including link $l_{(i,j)}$ in Figure 2) [8] [9].

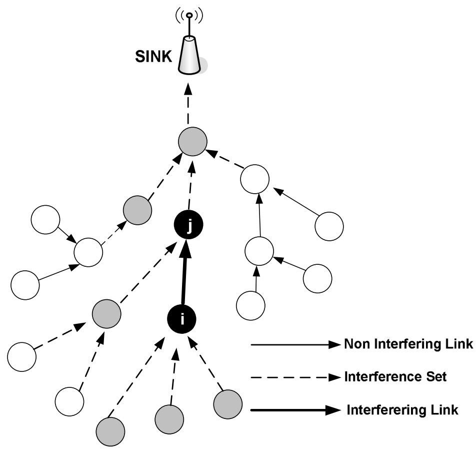

Fig. 2. Interference set for link $l_{(i,j)}$

Definition 3: It is considered that different traffic flows f_s exist in the network over time. Each traffic flow f_s initiates from individual source node $s \subseteq S$, where S is the set of source nodes. Different traffic flows may have common forwarding nodes or forwarding radio links on the way to the sink.

Definition 4: Given a buffer at each sensor node, runtime buffer size is the average buffer length at each epoch t. It is denoted as avg_i^t for a sensor node i. Using the exponential weighted moving average (EWMA) formula the runtime buffer size calculated as:

$$avg_i^t = w * avg_i^{t-1} + (1 - w) * avg_i^t \quad (1)$$

Here, $0 \leq w \leq 1$ and we use $w = 0.3$ for simulation.

4 Capacity Estimation Model

Wireless sensor networks comprise with varying traffic loads and different link capacity due to different transmission rates of upstream nodes and variet of interference levels respectively. In [10] Jaewon Kang et. al. showed that in a sub-topology or sub-network, congestion sum is the highest for the bottleneck link and capacity of bottleneck link reveals the overall capacity fraction of the sub-network. So it demonstrates that bottleneck link over a path and its surrounding nodes/links are vulnerable to congestion. In this paper, this vulnerable bottleneck links are though to be the in-network hot spots. In order to control congestion and maintain the path's minimum capacity, rate control in corresponding sender nodes is necessary. Hence our goal is to find out each link's states (vulnerable to congestion or not) for all active links and accordingly perform rate control over them.

4.1 Transmission Interval

A CSMA MAC protocol [2] is supposed to give fair channel access to all the nodes with equal probability. The MAC protocol includes contention technique for accessing the idle channel by a backlogged node and send data to its receiver. Each receiver node acknowledges its sender node after successfully reception of a data packet. In this protocol we define a metric called transmission interval $TI^t_{l(i,j)}$ for each link $l_{(i,j)}$ (also called transmission interval of node i). It includes the total transmission time of data packets from node i destined to node j, reception of those data packets at node j, transmission/reception time of each of the nodes (endpoints) belonging to the radio links in interfering set $inf_{l(i,j)}$. Each node calculates its own transmission interval over network operation time and it is expected that $TI^t_{l(i,j)}$ will vary a lot over time with multiple values.

In Flush [1] it is shown, if interference range is twice than the transmission range then safe interval between two transmissions on a single path can be calculated. Thus it gives us an approximation that through overhearing immediate neighbour's transmission each node can be aware of their two-hop neighbour's transport information (current transmission interval)[13]. Let consider another metric minimum transmission interval (MTI^t_i) for node i while transmitting data on the link $l_{(i,j)}$:

$$MTI^t_i = Max(TI^t_{l_{(i,j)}}) \qquad \forall l_{(p,q)} \subseteq inf_{l_{(i,j)}} - l_{(i,j)} \tag{2}$$

In fact, MTI^t_i is the maximum transmission interval among all the links of interference set $inf_{l_{(i,j)}}$ except radio link $l_{(i,j)}$. Each node i will overhear the transmission interval of its neighbour nodes, whose corresponding links are in the interference set $inf_{l_{(i,j)}}$.

4.2 Link Capacity Estimation

In order to estimate link capacity, we use aggregated transmission interval Agg ($TI^t_{l_{(i,j)}}$) for link $l_{(i,j)}$ at an epoch time t. Aggregated transmission interval ($Agg(TI^t_{l_{(i,j)}})$) adds up all node's (or link's) transmission interval ($TI^t_{l_{(i,j)}}$) those are in the interference set ($inf_{l_{(i,j)}}$):

$$Agg(TI^t_{l_{(i,j)}}) = \sum_{l_{(p,q)} \subseteq inf_{l_{(i,j)}}} TI^t_{l_{(i,j)}} \tag{3}$$

The basis for deriving aggregated transmission interval is related with the principle of CSMA MAC [2] protocol where within the same interference range only one node can transmit at any given time. Therefore for link $l_{(i,j)}$ capacity will vary over time and according to capacity estimation method of [12]:

$$C^t_{l_{(i,j)}} = \frac{Min(MTI^t_i, MTI^t_j)}{Agg(TI^t_{l_{(i,j)}})} \tag{4}$$

Where, $C^t_{l_{(i,j)}}$ is the variable capacity of link $l_{(i,j)}$ at time epoch t.

5 Capacity Aware Data Transport

Proposed data transport protocol comprise with multiple approaches in order to get maximal channel utilization. In earlier discussion we argued that varying link capacity and congestion are closely coupled at the hot spot region of a network. Therefore, an efficient approach to detect the congested links derived in this section in order to perform rate control. Link capacity estimation of previous section works here as a prerequisite for congestion detection.

5.1 Congestion Detection

Let transmission rate of node i at time epoch t is r_i^t. Both parameters, transmission rate (r_i^t) and minimum transmission interval (MTI_i^t) of node i are closely related as:

$$r_i^t = \frac{1}{MTI_i^t} \tag{5}$$

In earlier definition, same intermediate nodes or same intermediate links are assumed to transmit multiple data flows (f_s) from different sources. Important feature to look at, traffic loads of a link $l_{(i,j)}$ should not exceed the capacity $C^t_{l_{(i,j)}}$:

$$\sum_{s \subseteq S} f_s * r_i^t = \sum_{s \subseteq S} \frac{f_s}{MTI_i^t} \leq C^t_{l_{(i,j)}} \tag{6}$$

Where, f_s is the flows passing through node i or link $l_{(i,j)}$. We define a metric *Congestion Detector* (CD) for each link and following condition express the state of link $l_{(i,j)}$ at time t:

$$CD^t_{l_{(i,j)}} = \begin{cases} True; & \sum_{s \subseteq S} \frac{f_s}{MTI_i^t} - C^t_{l_{(i,j)}} > 0 \\ False; & otherwise \end{cases} \tag{7}$$

5.2 Proposed Rate Control Scheme

In this scheme we propose an algorithm which performs rate control on each active links (more specifically on sender side of the active links). This approach helps us to achieve maximum utilization of the channel. Moreover as our congestion detection mechanism is based on interference and traffic loads (in terms of data flows), therefore it gives a very logical and practical thought for controlling the rate. Proposed algorithm comprises node level rate control considering both wireless channel capacity estimation and buffer occupancy of sensors.

In the rate control algorithm, node's (or link's) congestion state and buffer state are considered while selecting the suitable transmission rate (r_i^t) for node i. A rate *increase/decrease factor* (ϕ_i) used in order to adapt the rate:

$$\phi_i = avg_j^{t-2} - avg_j^{t-1} \tag{8}$$

Here, avg_i^{t-1} and avg_i^{t-2} are the runtime buffer sizes of receiving node j (immediate downstream node of i) on link $l_{(i,j)}$ at epoch time $(t-1)$ and $(t-2)$ respectively.

Algorithm. Rate Control Algorithm

/* r_i^t is the transmission rate of node i at time epoch t */
/* $CD_{l_{(i,j)}}^t$ is the *Congestion Status* of node i at time epoch t */
/* ϕ_i is the rate *increase/decrease factor* of node i */

1. **for** each link $l_{(i,j)} \subseteq$ **active do**
2.   **if** $\left\{(CD_{l_{i,j}}^t = True)\ \&\&\ (\phi_i < 0)\right\}$
3.   **set** $r_i^t = \frac{r_i^{t-1}}{2}$
4.   **else if** $\left\{(CD_{l_{i,j}}^t = True)\ \&\&\ (\phi_i \geq 0)\right\}$
5.   **set** $r_i^t = r_i^{t-1} - \phi_i$
6.   **else if** $\left\{(CD_{l_{i,j}}^t = False)\ \&\&\ (\phi_i < 0)\right\}$
7.   **set** $r_i^t = r_i^t$
8.   **else if** $\left\{(CD_{l_{i,j}}^t = False)\ \&\&\ (\phi_i \geq 0)\right\}$
9.   **set** $r_i^t = r_i^{t-1} + \phi_i$
10.   **such that** $r_i^t < MxRate$
11.   **end if**
12. **end for**

In the algorithm; first, if any active link found to be in congestion state with a negative value for the rate *increase/decrease factor* then proposed algorithm eventually makes multiplicative decrease for r_i^t on the sender side. Like AIMD, it just makes half of the previous rate so that packet drop rate can be eventually reduced. Second, if same link is found congested but with positive *increase/decrease factor* (line 4) then the rate is decreased as shown in line 5. Third, the rate does not change for sender nodes of the links which are in non-congestion state with a negative *increase/decrease factor* (line 6). Finally, for the non-congestion state and positive *increase/decrease factor* (line 8) additive rate increment is performed in line 9. Increment of transmission rate always bounded by a threshold $MxRate$, which is the maximum allowable rate from the receiving end of the link.

6 Performance Evaluations

Extensive simulations are performed in order to derive the performance of the proposed data transport scheme. Metrics like packet delivery ratio for different node density, run time buffer occupancy estimation, packet delivery latency are derived using the simulation results. In our simulation environment, CSMA MAC [12] protocol is used for ensuring equal chance of accessing channel for each node. We placed 100 nodes randomly in 50 x 50 m^2 and 100 x 100 m^2 area

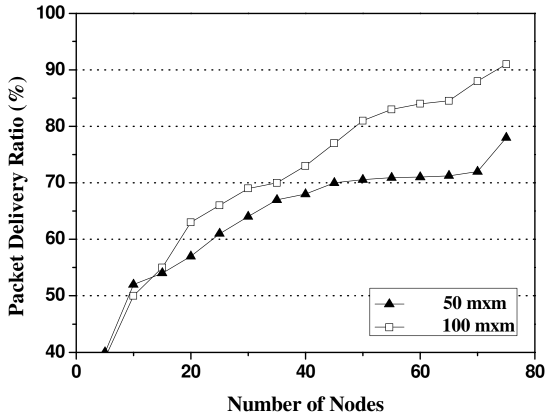

Fig. 3. Packet Delivery Ratio Based on Different Node Density Scenario

respectively. The transmission range and interference range are considered as $30m$ and $70m$ respectively. The maximum channel bandwidth/capacity is 256 *kbps* and generated packets have a size of 30 bytes. Total simulation run time is 90 seconds and duration of time epoch (t) considered to be 15 seconds. In our simulation total number of data flows varies from 4 to 8.

6.1 Packet Delivery Ratio

Packet delivery ratio includes the ratio between packets that successfully received at sink and total number of packets that generated from the sources. In Figure 3 it can be seen that, proposed rate control gives a fair raise in case of packet delivery ratio (up to 90 percentage for 100 x 100 m^2 area) over simulation time. Consideration of link interference and traffic load for rate control ensures the increasing delivery ratio.

In the figure we point out the relationship between packet delivery ratio and node density. Here on x-axes node density scenarios includes an average number of nodes in 50 x 50 m^2 and 100 x 100 m^2 terrains respectively. The summarized results of the graph demonstrate that in case of high node density the delivery ratio is quite low where as for sparse network (100 x 100 m^2 scenario) it shows better output. Probability of interference between nodes in a sparse network is low thus performance will be better in sparse network which in turn justifies our protocols principle.

6.2 Runtime Buffer Size

In our simulation we assume that a node can hold maximum 10 packets having the same as its buffer size. Simulation run time average buffer sizes of intermediate nodes are plotted in Figure 4. Results shown here are the average values over time for intermediate nodes between source and destination pairs in the

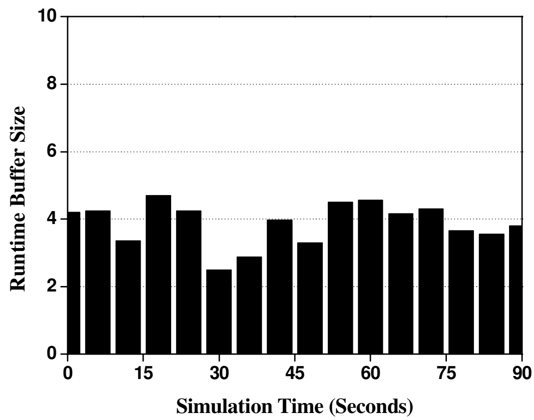

Fig. 4. Runtime Buffer Size Scenario

network. It shows the average maximum runtime buffer size reaches around 5 packets which indicates a moderate buffer size to control congestion. Concept of immediate distributed rate control over the congested links ensures reducing packet loss due to buffer overflow.

6.3 End-to-End Latency

In the simulation, in network end-to-end packet delay is considered as the latency. The experimental output for latency can be seen in Figure 5, where proposed data transport scheme ensures a noticeable low latency for delivering packet to the sink. Proposed data transport shows a reasonable average

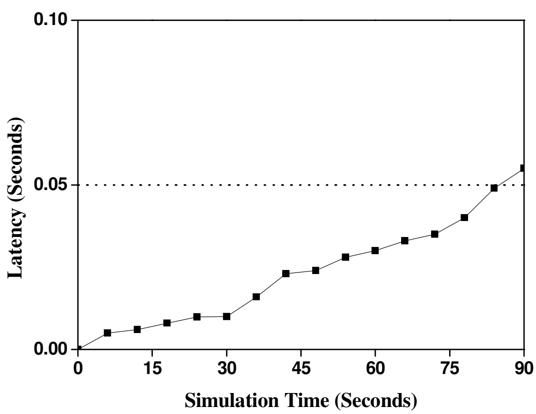

Fig. 5. End-to-End Latency for Packet Delivery

end-to-end delay which maintains a bound less than 0.05 seconds over the simulation time.

7 Conclusions

A sensor node with in a network contends for shared medium access and observes variation for link capacity due to interference. Wireless channel capacity varies over time due to interference and subsequently it has an impact on buffer occupancy of the sensor nodes. In sensor networks, these two factors caused packet loss while congestion occurs on intermediate nodes, which incurs less network throughput and performance degradation. This paper addresses the same phenomena and tried to find possible solution through a capacity aware data transport protocol. This scheme is verified to be an efficient one in terms of packet delivery ratio, packet delivery latency and runtime buffer size of sensor nodes. We believe our proposed scheme gives a perceptible performance and can contribute in data transport system for sensor networks.

References

1. Kim, S., Fonseca, R., et al.: Flush: A Reliable Bulk Transport Protocol for Multihop Wireless Network. Technical Report UCB/EECS-2006-169, EECS, University of California, Berkeley (2006)
2. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; ANSI/IEEE Std. 802.11 1999 Edition (1999)
3. Rangwala, S., Gummadi, R., Govindan, R., Psounis, K.: Interference-Aware Fair Rate Control in Wireless Sensor Networks. In: Proc. ACM SIGCOMM Symposium on Network Architectures and Protocols (2006)
4. Bian, F., Rangwala, S., Govindan, R.: Quasi-static Centralized Rate Allocation for Sensor Networks. In: Proc. IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON) (2007)
5. Sankarasubramaniam, Y., Akan, O.B., Akyildiz, I.F.: ESRT: Event-to-sink Reliable Transport in Wireless Sensor Networks. In: Proc. 4th ACM international symposium on Mobile ad hoc networking & computing (MobiHoc 2003) (2003)
6. Wan, C.-Y., Eisenman, S.B., Campbell, A.T.: CODA: Congestion detection and avoidance in sensor networks. In: Proc. ACM SenSys. (November 2003)
7. Hull, B., Jamieson, K., Balakrishnan, H.: Mitigating Congestion in Wireless Sensor Networks. In: Proc. ACM Sensys. (November 2004)
8. Waharte, S., Farzan, A., Boutaba, R.: Min-Max Congestion in Interference-Prone Wireless Mesh Networks. In: Proc. of the IEEE ICC 2007 (2007)
9. Acharya, P.A.K., Sharma, A., Belding, E.M., Almeroth, K.C., Papagiannaki, K.: Congestion-Aware Rate Adaptation in Wireless Networks: A Measurement-Driven Approach. In: Proc. of IEEE SECON 2008 (2008)
10. Kang, J., Zhang, Y., Nath, B.: TARA: Topology-Aware Resource Adaptation to Alleviate Congestion in Sensor Networks. IEEE Trans. on Parallel and Distributed Systems 18(7) (July 2007)

11. Paek, J., Govindan, R.: RCRT: rate-controlled reliable transport for wireless sensor networks. In: Proc. of ACM SenSys., NSW, Australia, pp. 305–319 (2007)
12. Tehuang, L., Wanjiun, L.: Capacity-Aware Routing in Multi-Channel Multi-Rate Wireless Mesh Networks. In: Proc. of IEEE ICC 2006 (2006)
13. Kohvakka, M., Suhonen, J., Kuorilehto, M., Kaseva, V., Hannikainen, M., Hamalainen, T.D.: Energy-efficient neighbor discovery protocol for mobile wireless sensor networks. Ad Hoc Networks 7(1), 24–41 (2009), `www.sciencedirect.com`