QoS integrated energy aware routing for wireless sensor networks

J. Reshma*

Department of Computer Science and Engineering,
BNM Institute of Technology,
Bengaluru, India
Email: reshmaj17@gmail.com
*Corresponding author

Satish Kumar T

Department of CSE,
BMS Institute of Technology and Management,
Bengaluru, India
Email: satish.savvy@gmail.com

R. Krishna Prasad

Department of Computer Science and Engineering,
Global Academy of Technology,
Bengaluru, India
Email: krishna.prasad@gat.ac.in

Abstract: Quality of service (QoS) in wireless sensor networks (WSNs) has got limited attention due to multiple bottlenecks such as limited bandwidth and energy storage. Until now, most of the focus has been to develop energy efficient routing schemes for WSN. It is important to provide effective QoS mechanism along with energy efficient data transmission. In this work, QoS mechanism is incorporated inside energy aware routing protocol proposed in Shah and Rabaey (2002). This new integrated protocol achieves dual goal of energy efficient data transmission and effective QoS functionalities. Empirical results are demonstrated on NS3 simulator. The proposed approach is compared against existing state of the art technique. The proposed approach outperforms the existing state of the art technique in prolonging the network lifetime.

Keywords: quality of service; QoS; energy efficiency; energy aware routing.

Reference to this paper should be made as follows: Reshma, J., Kumar T, S. and Krishna Prasad, R. (2020) 'QoS integrated energy aware routing for wireless sensor networks', *Int. J. Networking and Virtual Organisations*, Vol. 22, No. 1, pp.42–54.

Biographical notes: J. Reshma is Doctoral student in the Department of Computer Science and Engineering at BNM Institute of Technology, Bengaluru, India. She received her BE degree from the Bangalore University in 2001 and MTech from the Visvesvaraya Technological University in 2006. Her research is in the area of wireless sensor networks.

Satish Kumar T is a Professor of Department of Computer Science and Engineering at the Global Academy of Technology, Bengaluru where he has been since 2016. He received his BE degree from the Bangalore University in 2000, and ME degree from the Anna University at Chennai. He received his PhD in Computer Science from the Anna University in 2015. His research primarily focuses on code optimisation on high performance computing (HPC) systems. Specifically, using multi-core clusters with high degree of computations. Most of his interest lies in linking and combining code optimisation with machine learning. His work, while highly relevant to HPC is slowly picking up grounds in mobile computing and IOT. He has published in journals such as *Springer*, *International Journal of Applied Engineering Research* and *Asian Journal of Information Technology*.

R. Krishna Prasad is an Assistant Professor in Department of Computer Science at Engineering at the Global Academy of Technology, Bengaluru, India. He has published papers in international journals. He is planning to pursue research in the area of cloud computing with energy optimisation across data centres.

1 Introduction

The wireless sensor networks (WSNs) has undergone fast development due to the advances in wireless connectivity and device design. WSN have versatile applications in the area of vehicle traffic monitoring, environment observation, habitat monitoring, health applications, industry automation etc. The primary task of WSN is to collect information from its surrounding environment. To achieve this task, the sensor nodes are involved in continuous monitoring of the environment. Along with this primary task, the sensor nodes are also involved in data routing. Both functionalities of sensor nodes drain significant energy. Since, WSN in many cases are deployed in difficult terrain, wherein, constant energy supply is infeasible, the sensor nodes rely on stored energy reserves. This constraint of stored energy in sensor nodes enforces energy conservation requirement in WSN.

Currently, major research efforts are being invested for improving efficiency of WSN (Rabaey et al., 2000; Toh, 2001; Jain et al., 2001). Many approaches have been proposed to perform energy efficient routing (Perkins and Bhagwat, 1994; Jacquet et al., 2005). These approaches attempt to find the routing path which requires minimum energy. It was shown in Shah and Rabaey (2002) that, frequent usage of least energy cost path for routing large data can lead to network cliques. To overcome this problem, energy aware routing protocol (Shah and Rabaey, 2002) was proposed, in which, instead of using least energy path, multiple low energy paths were used.

1.1 Motivation

Currently, WSN cater to multiple applications. Some of them can be critical. For example, disaster monitoring application requires immediate reporting of the collected data. Otherwise, the counteractions might be ineffective. Hence, providing effective QoS with energy efficiency is essential in contemporary WSN.

There are multiple challenges in efficiently implementing QoS functionalities in WSN.

1 WSN are characterised by limited bandwidth, energy, memory, communication and processing capabilities.

2 In many cases, the node deployment in WSN is not deterministic. This results in extra effort for route and neighbour discovery.

3 Link failures or node crashes are quiet common in WSN. Therefore, QoS gets affected with network topology changes.

4 Node addition or removal can also affect the effectiveness of QoS.

The energy aware routing protocol primarily focuses on extending network lifetime. In contemporary WSN, the volume of data production is increasing rapidly, which makes utilisation of energy aware routing protocol extremely essential. However, this protocol does not include an effective QoS mechanism. Hence, the goal ahead is to extend energy aware routing protocol to include effective QoS mechanism.

1.2 Paper contributions

In this work, effective QoS mechanism is incorporated inside energy aware routing protocol (Shah and Rabaey, 2002). Two parameters: minimum required bandwidth and maximum delay are used for providing QoS. A new probabilistic mass function is proposed for routing of data packets which rewards those paths that have rich resources. The advantages of the proposed approach are demonstrated on NS3.

This paper is organised as follows: Section 2 provides the related work in this area. Section 3 illustrates the proposed approach. Section 4 provides the empirical results and Section 5 concludes the work with future problem in this area.

2 Research background

Due to persistent link and node failures in WSN, ad-hoc routing protocols have become quite popular. The specialty of these protocols is that, the nodes are involved in the creation of routing information. These protocols were basically developed for wireless transmission.

The ad-hoc routing protocols are broadly divided into proactive and reactive routing protocols. The proactive protocols maintain updated routing information between every pair of nodes in the network. Routing tables are maintained by the nodes to store routing information and topology changes are updated to all the nodes by propagating information through the network. The reactive protocols create routing information when desired. This requires initiation of route discovery process for creating the routing information. This initiation can be performed either by source or destination.

One of the popular proactive routing protocols is destination sequenced distance vector (DSDV) routing protocol (Perkins and Bhagwat, 1994). The shortest path between pair of nodes is calculated by Bellman Ford algorithm and every node maintains the next hop information to reach other nodes in the network. Also, this technique ensures that loops are not present in the routing information. The topology changes are intimated to the nodes which results in recreating the routing information.

Another popular proactive routing protocol is the Link state routing (Jacquet et al., 2005). Here, each node floods the network with cost information so that, every other node can use this cost information to compute the least cost paths. This protocol is adaptable even for unidirectional links whereas, DSDV requires bidirectional links.

The ad hoc on demand distance vector (AODV) routing (Perkins and Royer, 1999) is one of the popular reactive routing protocols. This protocol is similar to DSDV but, the source node initiates the route discovery by broadcasting route request packets (RREQ). The intermediate nodes which receive RREQ packets, rebroadcast these packets until the destination node is reached. The intermediate nodes record the neighbour information which sends the first RREQ packet. This mechanism helps in creating a reverse path.

Dynamic source routing (DSR) protocol (Johnson and Maltz, 1996) is another reactive protocol which is similar to AODV protocol. The main difference is that, after destination node receives the RREQ packet, route reply (RREP) packets are sent to the source node from the destination node. The RREP packets contain all the required path information to reach the destination node.

The directed diffusion protocol (Intanagonwiwat et al., 2000) is a reactive protocol which is application aware and data centric. It is a destination node initiated protocol. The destination node requests data by flooding the network with request packets. Each node which receives the request packet sets up a gradient/direction to the neighbour node which transmitted this packet. By using this gradient information, the nodes transmit data towards the destination. Since, multiple paths can be created to reach the destination node, the data transfer rate of a particular path is increased by sending positive reinforcement messages from the destination node.

All the above described routing schemes, attempt to establish the most energy efficient path between source and destination nodes. Energy conservation in sensor nodes is extremely important in-order to prolong the life of sensor nodes. So, any routing scheme has to address energy conservation problem (Chen and Varshney, 2004; Vali et al., 2004; Nabi et al., 2010; Zhou et al., 2007).

2.1 Energy aware routing for low energy ad-hoc sensor networks (Shah and Rabaey, 2002)

Most of the routing protocols in WSN concentrate on finding lowest energy route to setup communication with source and destination nodes. It was shown in Shah and Rabaey (2002) that, finding optimal energy path is not beneficial for prolonging network life time and long term connectivity. Usage of low energy path frequently can lead to energy draining of nodes in the path and can lead to partitioning of the network.

To address this problem, a new energy aware routing protocol was proposed in Shah and Rabaey (2002). To increase the life time of network, occasional choosing of suboptimal paths is necessary. It helps in preventing excessive energy depletion of nodes in the optimal path and provides resistance against partitioning of networks. This routing protocol is reactive and destination initiated protocol.

This energy aware routing protocol detects multiple paths between destination and source node. Each path has certain probability of being chosen and this probability is based on the current energy levels of the nodes. So, whenever a data packet is sent from source to destination, one of the feasible paths is chosen probabilistically. This routing mechanism by using different paths continuously prevents excessive energy depletion in the nodes of the optimal path.

This scheme has similarities with the diffusion protocol. The diffusion protocol sends data by using different paths at regular intervals, but energy aware routing is more adaptable in choosing different paths by using the energy status of the nodes. This helps significantly in avoiding paths which have low energy nodes.

This protocol has three stages.

1. Setup stage – in this stage, flooding of network is performed by the destination node to discover different paths and their associated energy cost to reach the source node. Routing tables also built in this stage.
2. Data propagation stage – the actual transmission of data packets are performed in this stage. The routing paths for each node are chosen probabilistically. The probability mass function utilises the energy costs that were calculated in the set up stage.
3. Route maintenance stage – the presence of link failures and energy depleted nodes are detected in this stage. Each node invokes localised flooding to update its routing information. But, this stage is performed infrequently.

2.1.1 Setup stage

1. The cost metric indicates the estimated energy cost incurred by a node to transmit a data packet. The cost of destination node N_d is initialised to 0 as shown in equation (1). The destination node initiates route discovery by flooding the network by RREQ packets.

$$\cos t(N_d) = 0 \tag{1}$$

2. Each intermediate node after obtaining RREQ packets, selects those neighbours which are closer to the source node and far away from the destination node. To accomplish this task, distance metric *d*() is utilised. The RREQ packet forwarding conditions used by the intermediate node N_i to neighbour are shown in equations (2) and (3). Here, N_s is the source node *and* N_d is the destination node.

$$d(N_i, N_s) >= d(N_j, N_s) \tag{2}$$

$$d(N_i, N_d) <= d(N_j, N_d) \tag{3}$$

3. The function *Energy_metric* is used by the intermediate node to calculate C_{N_j, N_i}, which is the energy cost of transmitting a data packet from node N_j to N_i. This computation is shown in equation (4). The description of the *Energy_metric* function is shown in Equation 5. Here, e_{ji}^{α} is the required energy to transmit a data packet from N_j to N_i, R_j is the residual energy of N_j, α and β are the weighting factors.

$$C_{N_j, N_i} = Cost(N_i) + Energy\_metric(N_j, N_i) \tag{4}$$

$$Energy\_metric(N_j, N_i) = e_{ji}^{\alpha} R_j^{\beta} \tag{5}$$

4. High cost paths are discarded and only low cost paths are added to the forwarding table of N_j. The forwarding table FT_j is constructed by using the condition illustrated in equation (6).

$$\mathrm{F}T_j = \left[i \mid C_{N_j, N_i} <= \alpha\left(\min_k C_{N_j, N_k}\right)\right] \tag{6}$$

5 Routing probabilities are assigned by N_j to all the nodes present in the forwarding table which is shown in equation (7).

$$P_{N_i, N_j} = \frac{\frac{1}{C_{N_j, N_k}}}{\sum_{k \in FT} \frac{1}{jC_{N_j, N_k}}} \tag{7}$$

6 The function cos$t(N_j)$ reflects the energy cost of using to forward the data packets. This cost function is the expected cost of all the neighbours present in the forwarding table. The cost calculation is illustrated in equation (8).

$$\cos t\left(N_j\right) = \sum \sum_{i \in FT_j} P_{N_j N_i} C_{N_j N_i} \tag{8}$$

7 This cost metric cos$t(N_j)$ is stamped to the RREQ packet and forwarded in the network.

2.1.2 Data communication stage

1 Initially, the source node transmits its data message by randomly choosing one of the neighbours in the forwarding table. The probability mass function for performing this task is based on the probability calculated for each neighbour in the set up stage.

2 Every intermediate node performs the same act of randomly choosing the neighbour based on the probability calculated in the previous stage.

3 After all data packets reached destination, the data communication stage ends.

It was highlighted in Azharuddin and Jana (2015), Rios and Diguez (2014), Mir et al. (2015), Xu et al. (2015), Semchedine et al. (2015), Alskaif et al. (2015), Zhang et al. (2015), Jardak et al. (2010), Fan et al. (2013), Al-Karaki et al. (2004) and Al-Karaki and Kamal (2004) that, contemporary WSN are catering to myriad of applications, and are also generating large quantities of data. Currently, in the literature, design of QoS mechanisms for low energy multipath routing in WSN has not been effectively achieved.

3 QoS integrated energy aware routing

In this work, two QoS parameters namely: minimum bandwidth required and tolerated maximum delay are incorporated into the energy aware routing protocol proposed in Shah and Rabaey (2002). The minimum bandwidth constraint wants every node in the selected path to provide the required minimum bandwidth. Each node in the WSN may enforce some delay in routing packets. This can occur due to packet being buffered at the intermediate nodes. The maximum delay constraint wants the maximum total delay experienced by the data packet should be within the value provided by this constraint.

The new algorithm which incorporates QoS inside energy aware routing also involves three stages. The set up stage employs flooding initiated by the destination node to discover feasible paths from source to destination, which also satisfy the two QoS constraints. The data communication stage randomly selects a feasible path from the available set of paths. The paths which have high energy nodes, more bandwidth and low buffer delays will be assigned higher probabilities so that weak resource paths can be protected from resource depletion. The route maintenance stage is invoked infrequently to update routing information.

3.1 Setup stage

1 The destination node initiates the route discovery process by including the information about required minimum bandwidth (mbw) and maximum delay (md) in RREQ packets. The cost of the destination node is set to 0 as shown in equation (1).

2 Consider an intermediate node N_j which has received RREQ packet from node N_i. Let, d_j be the maximum delay offered for a data packet and b_j be the bandwidth offered by N_j. This node forwards the RREQ packet if the conditions shown in equations (9) and (10) are satisfied. If these two conditions are satisfied, then the new value md = md-d_j is stored in the RREQ packet for rebroadcasting. The node N_j selects all the neighbours to forward the RREQ packet. In the old technique [13], neighbour nodes which were closer to the source node and far away from destination node were selected. This scheme is not adapted in this work because there might be very few neighbour nodes which might satisfy the given QoS constraints. So, using this scheme may filter out all the feasible paths. Also, node N_i will store its maximum delay offered d_i and available bandwidth b_i information in the RREQ packet before sending it to node N_j.

$$b_j \geq mbw \tag{9}$$

$$\text{md-}d_j \geq 0 \tag{10}$$

3 If the forwarding conditions shown in equations (9) and (10) are satisfied then, node N_j calculates the cost of the path from $N_j \rightarrow N_i$ using equations (4) and (5).

4 As mentioned above, there might be very few feasible paths which might satisfy the QoS constraints. If the high energy cost paths are discarded by using equation (6) then, it may result in no available feasible paths to perform data transmission. To optimise this situation, a threshold parameter T_p is utilised. If the number of feasible paths from N_j is lesser than T_p then, all the paths are added into the forwarding table FT_j otherwise, the forwarding table is created by using the equation (6).

5 The probability of forwarding a data packet to neighbour N_i present in FT_j is shown in equation (11). This calculated probability is stored in the forwarding table FT_j. Here, d_k and b_k are the maximum delay offered and available bandwidth for node N_k which is present in the forwarding table FT_j

$$P_{N_j,N_i} = \frac{\dfrac{b_i}{C_{N_j,N_i} + d_i}}{\sum_{k \in FT_j} \dfrac{b_k}{C_{N_j,N_k} + d_k}} \tag{11}$$

6 The cost of node N_j is calculated by using equation (8) and stored in the RREQ packet along with d_j and b_j. This RREQ packet is again rebroadcasted.

3.2 Data communication stage

1 The source node randomly selects one of the feasible path from the forwarding table by using the probability mass function shown in equation (11). This probability mass function rewards those neighbours which provide more bandwidth than the required minimum bandwidth. Also, it penalises those neighbours which contribute higher delay or require higher energy cost to receive the data packets. This mechanism ensures that those paths which have rich resources to satisfy QoS constraints incur low transmission energy costs and have sufficient remnant energy in the nodes have higher chance of being selected.

2 Every intermediate node which is part of the feasible path to reach destination, upon receiving the data packet, selects one of the neighbour from the forwarding table by using the probability mass function shown in equation (11).

The complete QoS integrated energy aware routing is illustrated in Algorithm 1 and Figure 1 illustrates the algorithm flow diagram.

Algorithm 1 QoS integrated energy aware routing

[Source node]

If Received RREQ packet **then**

Create the forwarding table by using equation (11)

end if

If Need to transmit data packet **then**

Randomly select one of the neighbours by using the probability mass function shown in equation (11).

End if

[Intermediate node]

If Received RREQ packet and QoS conditions in Equations 9 and 10 are satisfied **then**

Update the forwarding table and RREQ packet by using step 2, 3, 4, 5 and 6 of the set up stage.

End if

If received a data packet **then**

Randomly select one of the neighbours by using the probability mass function shown in equation (11).

End if

[Destination node]

If need to discover feasible paths to source node **then**

Create the RREQ packet by including information about md, mbw and cost information shown in equation (1)

Perform broadcasting of RREQ packets to the neighbours

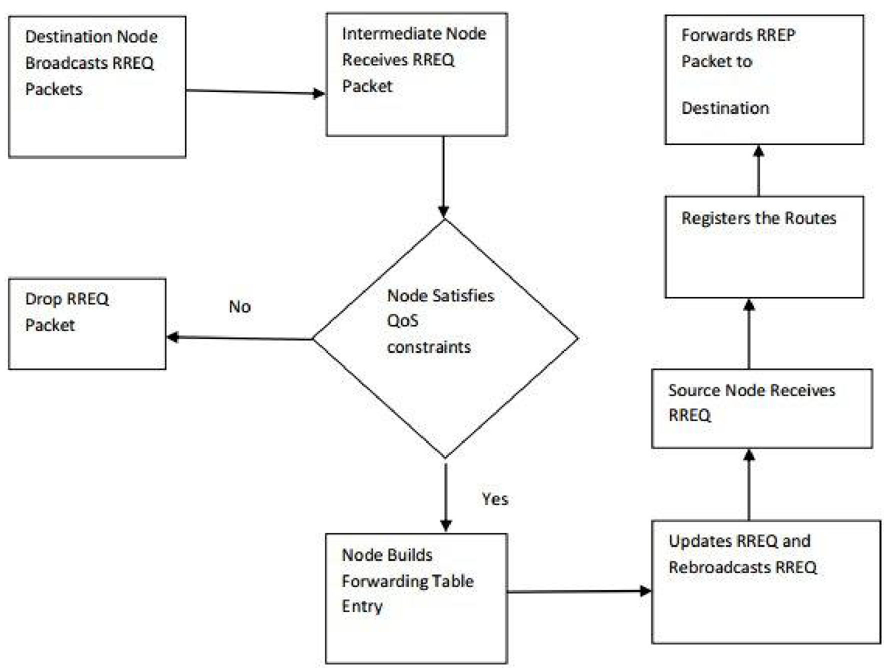
End if

If data packet is received **then**

Process the data packet and stop routing of this data packet.

End if

Figure 1 Algorithm flow diagram



The correctness of the proposed QoS integrated energy aware routing protocol technique is presented in Theorem 1.

3.3 Theorem 1 (algorithm correctness)

The proposed extension for energy aware routing protocol will always select those paths which satisfy the QoS constraints specified by A.

Proof. The proof is by contradiction. Suppose, there is some path P_i which is selected by the proposed scheme, which does not satisfy the specified constraints *mbw* or *md*, then, there is at-least one node $N_j \in P_i$ which has either $b_j < mbw$ or $d_j > md$. But, such node cannot be selected in the route discovery stage of the proposed scheme, because of filtering mechanism implemented by equations (9) and (10).

4 Results and discussions

The experiments were carried out in NS3 simulator. The proposed QoS integrated energy aware routing algorithm (EAWQ) was compared against QoS integrated best path routing mechanism (BPQ) (Perkins and Bhagwat, 1994; Jacquet et al., 2005). The BPQ approach integrates the QoS component into the least cost path route discovery process.

Initially, WSN was simulated by using 100 sensor nodes. All the sensor nodes had varying current energy levels. The minimum current energy level of a sensor node was set to half of the battery capacity. Similarly, all nodes had varying bandwidth and buffer delays. The threshold parameter T_p was set to five. The metric average energy consumed (avgc) shown in equation (12) is used in the experiments. Here, n_i represents one of the node belonging to the data transmission path, $energy\_expense(n_i)$ is the amount of energy used by node to complete data transmission of group of packets and N are the number of nodes involved in data transmission. This metric illustrates the average energy consumed by the nodes involved in data transfer. It is calculated after group of packets complete their transmission.

$$Avgc = \sum_{ni} \frac{energy\_expense(n_i)}{N} \tag{12}$$

Figure 2 illustrates the performance of EAWQ and BPQ when varying number of data packets are involved in transmission. It is clear that, *avgc* of EAWQ is much lower than BPQ since, for each data packet different nodes are involved in transmission. For BPQ, the nodes of the least cost path are always involved in data transmission so, avgc is much higher. This indicates that chances of network partitioning through energy depletion of nodes by BPQ are always higher.

Figure 2 Avgc vs. no. of data packets (see online version for colours)

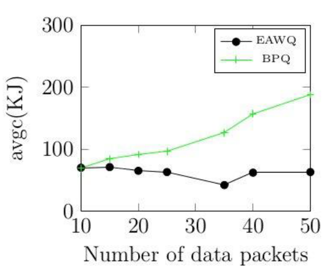
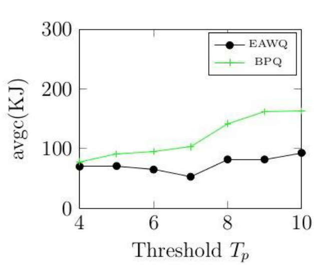


Figure 3 Avgc vs. T_p (see online version for colours)



The performance of EAWQ and BPQ against different threshold values with respect to avgc is illustrated in Figure 3. Again, EAWQ outperforms BPQ in prolonging the network life time.

Figures 4 and 5 illustrate the performance of BPQ and EAWQ when QoS parameters are varied. As expected, EAWQ provides benefits with respect to avgc metric, but as the value of QoS parameters increase, performance of EAWQ decreases, because of the reduction in number of feasible paths. This results in having few options to distribute data packet load, which increases avgc value.

Figure 4 Minimum bandwidth vs. avgc (see online version for colours)

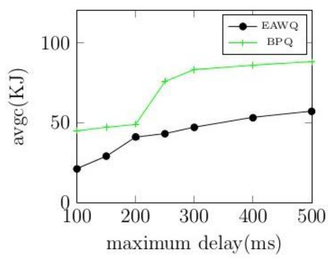


Figure 5 Avgc vs. maximum delay (see online version for colours)

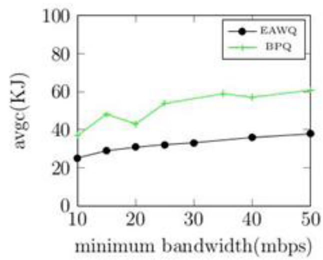


Figure 6 illustrates the avgc performance of BPQ and EAWQ with varying number of nodes in the network. The number of data packets was fixed at 50. As the network size increases, more options are available for EAWQ to perform energy aware routing. Hence, with increase in network size, avgc decreases for EAWQ. This experiment is again repeated by fixing data packets at 100 and similar results are obtained as shown in Figure 7.

Figure 6 No. of nodes (ndp = 50) vs. avgc (see online version for colours)

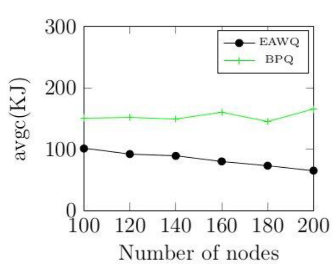
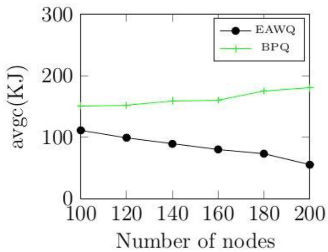


Figure 7 No. of nodes (ndp = 100) vs. avgc (see online version for colours)



5 Conclusions

In this work, quality of service component is integrated with energy aware routing. Two quality of service parameters namely: minimum required bandwidth and maximum delay have been addressed. The proposed approach not only provides shield against network disconnection, but also provides efficient routes to perform data delivery. One of the important lessons learnt during the design of the proposed routing technique is that the energy aware routing protocol and in general multipath routing protocols provide high degree of flexibility in adapting these protocols for future performance requirements. Such flexibility is quite often not seen in other routing protocols which are largely deviated from energy aware routing protocol. However, the proposed routing technique still does not address the Big Data issues in which the sensor nodes are involved in the production of big data and which is going to become commonplace in future WSN. The proposed routing protocol still cannot scale up to address big data issue and requires redesigning to achieve the said goal.

In future, new QoS parameters such as jitter, congestion probability, etc. need to be incorporated so that various QoS services along with efficient data transmission can be provided. Energy aware routing also needs to be extended to address the criticality of the applications. Some of the applications might be critical and require strict QoS, but some applications might tolerate slight variation in the requested QoS. Hence, a framework to extend energy aware routing to achieve this goal needs to be designed in future.

References

Al-Karaki, J.N. and Kamal, A.E. (2004) ‘On the correlated data gathering problems in wireless sensor networks’, to appear in the *Proceedings of The Ninth IEEE Symposium on Computers and Communications*, July, Alexandria, Egypt.

Al-karaki, J.N., Ul-Mustafa, R. and Kamal, A.E. (2004) ‘Data aggregation in wireless sensor networks-exact and approximate algorithms’, *Proceedings of IEEE Workshop on High performance Switching and Routing (HPSR) 2004*, 18–21 April, Phoenix, Arizona, USA.

Alskaif, T., Zapata, M.G. and Bellalta, B. (2015) ‘Game theory for energy efficiency in wireless sensor networks’, *Journal of Network and Computer Applications*, August, Vol. 54, pp.33–61.

Azharuddin, M. and Jana, P.K. (2015) ‘A distributed algorithm for energy efficient and fault tolerant routing in wireless sensor networks’, January, Vol. 21, No. 1, pp.251–267.

Chen, D. and Varshney, P.K. (2004) 'QoS Support in Wireless Sensor Networks A survey', *Proceedings of the 2004 International Conference on Wireless Networks*, Las Vegas, USA, 21–24 June.

Fan, T., Zhang, X. and Gao, F. (2013) 'Cloud storage solution for WSN in internet innovation union', *International Journal of Database Theory and Application*, June, Vol. 6, No. 3, pp.33–61.

Intanagonwiwat, C., Govindan, R. and Estrin, D. (2000) 'Directed diffusion: a scalable and robust communication paradigm for sensor networks', in *IEEE ACM Mobicom*, pp.56–67.

Jacquet, P. et al. (2005) *Optimized Link State Routing in Internet draft* [online] http://www.ietf.org/internet-drafts/draft-ietf-manet-oslr-04.txt (accessed 3 July 2017).

Jain, R., Puri, A. and Sengupta, R. (2001) 'Geographical routing for wireless adhoc networks using partial information', in *IEEE Personal Comm.*, February.

Jardak, C., Riihijrv, J. and Oldewurt, F. (2010) *Parallel Processing of Data from Very Large-Scale Wireless Sensor Networks*, Aachen, Germany.

Johnson, D.B. and Maltz, D.A. (1996) 'Dynamic source routing in ad hoc wireless networks', in *Mobile Computing*, Kluwer, pp.153–181.

Mir, Z.H., Imran, S. and Ko, Y-B. (2015) 'Neighbor-assisted data delivery to mobile sink in wireless sensor networks', *Proceedings of the 9th International Conference on Ubiquitous Information management and Communication*, 8–10 January, Bali, Indonesia, pp.1–8.

Nabi, M., Blagojevic, M., Geilen, M. and Basten, T. (2010) 'MCMAC an optimized medium access control protocol for mobile clusters in wireless sensor networks', in *Proceedings of the 7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad-Hoc Communications and Networks*, Boston, USA, 21–25 June.

Perkins, C. and Royer, E. (1999) 'Ad hoc on demand distance vector routing', in *Proc. 2nd IEEE Wksp Mobile Comp. Sys AND Apps*, February.

Perkins, C.E. and Bhagwat, P. (1994) 'Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers', in *Comp. Commun. Rev.*,October, pp.234–244.

Rabaey, J.M. et al. (2000) 'Pico radio supports ad hoc ultra-low power wireless networking', in *IEEE Computer*, July, pp.42–48.

Rios, L.G. and Diguez, J.A.I. (2014) 'Big data infrastructure for an analyzing data generated by wireless sensor networks, *2014 IEEE International Congress on Big Data*, DOI: 978-1-4799-5057-7/14.

Semchedine, F., Bouallouche-Medjkoune, L., Tamert, M., Mahfound, F., Aissani, D. (2015) 'Load balancing mechanism for data-centric routing in wireless sensor networks', *Computers and Electrical Engineering*, Vol. 41, p.395–406.

Shah, R.C. and Rabaey, J.M. (2002) *Energy Aware Routing for Low Energy Ad Hoc Sensor Networks*, in Technical Support F29601-99-1-0169.

Toh, C.K. (2001) 'Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks', in *IEEE Comm. Mag.*, June, pp.138–147.

Vali, D., Paskalis, S., Kaloxylos, A. and Merakos L. (2004) 'A survey of internet QoS signalling', in *IEEE Common Survey Tutorials*, Vol. 6, pp.32–12.

Xu, J., Guo, S., Xiao, B. and He, J. (2015) 'Energy-efficient big data storage and retrieval for wireless sensor networks with non uniform node distribution', *Concurrency and Computation: Practice and Experience*, December, Vol. 27, No. 18, pp.5765–5779.

Zhang, S., Zhang, Q., Xiao, S., Zhu, T., Gu, Y. and Lin, Y. (2015) 'Cooperative data reduction in wireless sensor network, *ACM Transactions on Embedded Computing Systems (TECS)*, December, Vol. 14, No.14, p115–121.

Zhou, Y., Ngai, E.C.H., Lyu, M.R. and Liu, J. (2007) 'Power-speed: a power controlled real time data transport protocol for wireless sensor actuator networks', in *Proceedings of the IEEE Wireless Communications and Networking Conference*, Hong Kong, 11–15 March.