Structural Engineering and Mechanics, *Vol. 49, No. 4 (2014) 509-521*
DOI: http://dx.doi.org/10.12989/sem.2014.49.4.509

Wireless sensor network protocol comparison for bridge health assessment

Gokhan Kilic*

Department of Civil Engineering, Izmir University of Economics, Sakarya Cad. No.156, Balçova, 35330, Izmir, Turkey

(Received March 21, 2013, Revised December 30, 2013, Accepted January 12, 2014)

Abstract. In this paper two protocols of Wireless Sensor Networks (WSN) are examined through both a simulation and a case study. The simulation was performed with the optimized network (OPNET) simulator while comparing the performance of the Ad-Hoc on demand Distance Vector (AODV) and the Dynamic Source Routing (DSR) protocols. This is compared and shown with real-world measurement of deflection from eight wireless sensor nodes. The wireless sensor response results were compared with accelerometer sensors for validation purposes. It was found that although the computer simulation suggests the AODV protocol is more accurate, in the case study no distinct difference was found. However, it was shown that AODV is still more beneficial in the field as it has a longer battery life enabling longer surveying times. This is a significant finding as a large factor in determining the use of wireless network sensors as a method of assessing structural response has been their short battery life. Thus if protocols which enhance battery life, such as the AODV protocol, are employed it may be possible in the future to couple wireless networks with solar power extending their monitoring periods.

Keywords: wireless; AODV; DSR; bridges; non-destructive testing; structural health monitoring

1. Introduction

A crucial facet of bridge engineering is health monitoring, which aims to prevent the failure of structures and the consequences that it causes: loss of life, disruption and cost. It is therefore important to optimise all aspects of health monitoring to ensure their accuracy, applicability and cost in terms of both time and money. Bridges represent a major part of infrastructure, comprising thousands of structures that often vary in their construction; owing to their placement and purpose. Due to the demanding conditions and loads bridges experience, degradation of their structural integrity is inevitable.

Problems have been encountered in aging bridges throughout the world, typically built in the 1950s and 1960s, which need health monitoring to address avoidable further structural deterioration and financial expenditure. The risks involved with bridge health monitoring are not purely monetary; personal safety is of paramount importance, with bridge collapses occurring to this day. For example, during the monsoons just before the Commonwealth Games in September 2010 the footbridge connecting a car park with the Games' main stadium collapsed and at least 23

*Corresponding author, Assistant Professor, E-mail: gokhan.kilic@ieu.edu.tr; gkilic@hotmail.co.uk

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

construction workers were injured. With the risks being so high, a large area of research has been devoted to developing techniques whereby the health of the bridge can be assessed before it deteriorates enough to require high cost remedial work or even collapse (Walker 2010).

Conventional methods of bridge assessment within the context of health monitoring have proved to be inadequate in ascertaining the full extent of inflicted damage to structures. It is also widely appreciated that the complexity of bridge structures demands a more rigorous and thorough approach when the long term total integrity and functionality of these structures is required.

WSN is an advanced non-destructive technique that presents a convenient application or assessment method that measures dynamic or static displacement and vibration monitoring from several points of the structure with high sensitivity. The wireless system is also suitable for remotely measuring displacements of the structure under micro-tremors, traffic or wind loading Farhey (2006) and Kamel (2010).

Many civil engineering monitoring programmes utilise WSN. This technique was originally proposed to reduce the cost of installation in large-scale civil structures. The benefits seen were the freedom wireless technology provides, including quick and reconfigurable installations. Several structures have since had wireless monitoring systems installed. These structures include the Alamosa Canyon Bridge (New Mexico), Geumdang Bridge (South Korea), WuYuan Bridge (China) and Voigt Bridge (California) which all bear out the reliability of wireless sensors in structural monitoring (Chae *et al*. 2012).

A WSN system is made up of anywhere between a few, to thousands of wireless sensors. Several sensors will be set up in specific locations in order to record the environmental parameters before being transmitted to the central control for appraisal by operatives. These wireless sensors can be placed and then moved for convenience in offering low cost, flexible layouts (Lee *et al*. 2007). In monitoring bridges in real-time, five subsystems of networking are required, consisting of: sensor (information gathering) system, information transmission system, information processing system, information analysis system, system control and feedback (Guoa 2011).

The effectiveness of WSN is reliant mainly on its protocols which are defined as either proactive or routing. In order to develop an efficient system, the aim is to determine the optimum path to route packets to their destination while keeping resources utilisation to a minimum. This approach is problematic as the topology does not remain constant due to node movement, which results in the necessary minimization of control traffic generated by the routing protocols to create the best performance.

Previous research in this area has focussed on the theoretical simulation of protocol performance using OPNET software (Bello *et al*. 2011). Their findings indicated that the AODV protocol performed better than DSR in terms of both transferring data and battery life (Dwivedi *et al*. 2012). These findings have limitations however as they are purely simulation based and lack real world data for comparison. This is the gap in research which this paper serves to rectify, by evaluating and comparing these two protocols with WSN results for the deflection of HMS Chatham Bridge.

Thus, the main objective of this paper is to evaluate the performance of AODV and DSR routing protocols in relation to a WSN used to measure bridge deflection. This is assessed in terms of their ability increase throughput in a large capacity network while decreasing end to end delay with the presence of additional noise level (traffic, wind loading etc.).

In the following section, the site chosen, AODV and DSR protocols, related work and motivation are all discussed. Subsequent to this, a detailed WSN system for bridge and vehicle monitoring is presented and the results of the simulation and application of these protocols are shown.

Fig. 1 Location of the HMS Chatham Bridge (Google Maps 2010)

Fig. 2 HMS Chatham Bridge (Photos from Gokhan Kilic 2012)

2. Design and experimental methodology

2.1 Site description

HMS Chatham Bridge (Fig. 2) was constructed in 1996 and is located on Pembroke Road between Gillingham and St Marys Island in Chatham, Kent (Fig. 1) (Chatham Maritime House 2010).

The HMS Chatham Bridge is a three span construction comprising two concrete approach spans and a single leaf lifting bridge centre span. The bridge includes a 6.75m carriageway with a 3.0m combined footpath and cycleway on the west side and a 1.8m footpath on the east side. The two internal piers are connected to pile caps which are supported on bored piles. A visual inspection was completed by the author on 10 June 2012, which showed no signs of structural defects or anomalies. The weather was dry and sunny and the temperature was 16°C.

2.2 WSN routing protocols

DSR provides an effective and straight-forward source routing protocol in the place of hop-by-hop routing. Its on-demand “Route Discovery” and “Route Maintenance” mechanisms negate the need for intermediate nodes to maintain up to date routing information and neighbour detection, lessening bandwidth consumption. Rather, within the header of each routed packet lies instructions on the ordered pathway of nodes through which the packet must travel (Culler and Hong 2004).

Similar to DSR, AODV uses the on-demand “Route Discovery” and “Route Maintenance” routing mechanisms but it also utilises hop-by-hop routing sequence numbers and intermittent beacons from the Destination-Sequenced Distance-Vector (DSDV), as discussed at (Pirzada *et al*. 2006) and (Chang *et al*. 2005). The dynamic nature of AODV as an on-demand routing system for mobile wireless ad hoc networks has the ability to devise a new route where, for example, a source node “S” wants to route packets to a destination node “D” that does not already have the route.

This study proposes that a model be developed to analyse what the effects of ambient noise and path loss are on mobile ad hoc networks using optimized network (OPNET) simulation in terms of received signal strength. Simultaneously, AODV and DSR protocol comparisons will take place. A simulation took place using the OPNET simulator within a physical topology area of 60m × 8m using a random way point mobility model, by way of validation of the developed model. Initially, each node hesitates for a pause time, before travelling towards a destination at speeds of 0 to 20 meters per seconds. At its destination, the node hesitates once again before repeating this process, until the end of the simulation period. Fig. 3 shows 8 node mobility model which have pause times of 100, 200, 400, 600, 800, and 900 seconds respectively and a maximum speed of 10 meters per second. Traffic in the network is generated by Constant Bit Rate (CBR) agents and packet sizes of 1000 bytes.

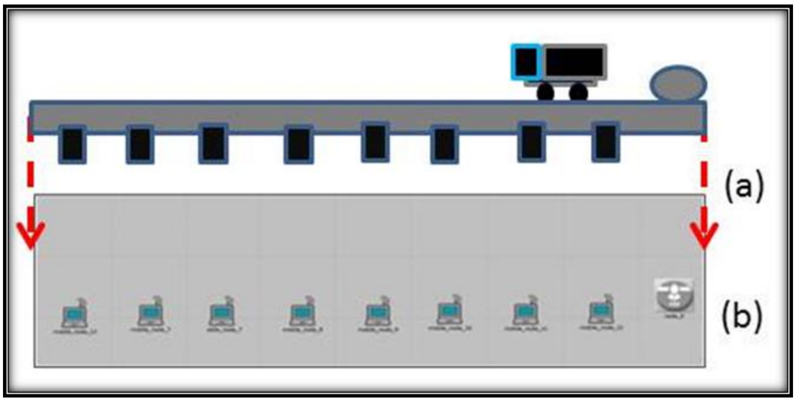

Fig. 3 (a) Wireless sensor nodes locations and (b) OPNET modelling

Table 1 Simulation parameters

Parameters	Values
Channel type	Wireless channel
Physical characteristics	802.11g
Data rate	2Mbs
Topology	60 m × 8 m
Routing protocol	AODV, DSR
Number of sensor nodes	8
Transmit power	1.6 W
Packet Size	512 bits
Simulation time	300seconds
Traffic source	CBR

It can be seen that altering the network’s mobility model and power control system results in the network protocol performing very differently. See Table 1 for AODV and DSR simulation parameters. These have been set to mimic the characteristics of the HMS Chatham Bridge structure. Of note is the use of a 2Mbs data rate that aims to be representative of the most common data rate from all of the nodes when a measurement is being taken.

In this a paper the wireless sensor nodes used are provided by Oracle, which is a company that provides wireless sensor solutions to various applications with a software kit for flexible implementations. An Oracle WSN is a self-organised and infrastructure-less wireless network, and as such is preferred for this type of health monitoring activity (Oracle Corporation 2012).

2.3 WSN for bridge and vehicle monitoring

WSNs have been shown to be a relatively reliable monitoring system in the area of structural health monitoring. The monitoring of civil structures produces much sensor data in its search for anomalies and this causes some constraints in terms of resources (Basharat *et al*. 2005).

Bridge response monitoring with wireless sensor nodes comprises of gathering and assessing structural behaviour under either static or dynamic loading. This is accomplished by gathering results at a particular node for centralized processing. Much attention has been directed to the use of wireless sensor technology due to the fact that it is low cost, has computational resources for sensor-based data processing and is easily installed for use in large structures Kim and Lynch (2012), Lee *et al*. (2007) and Guoa (2011).

Experimental load ratings and measurements can offer calculations of the load carrying capacity of operational structures. These test routines also appraise the quasi-static response of the bridge in key areas such as neutral axis locations and load shedding paths in indicating structural performance. Load ratings require the structure to cease operation and the loading of vehicles of known weight and therefore this procedure is considered a periodic, schedule-based application rather than continuous monitoring (Whelan 2009).

Fig. 4 shows an Oracle wireless node which runs on a Java embedded software development platform without an operating system. In this study, the Oracle Sun Spot wireless sensor nodes were installed on HMS Chatham Bridge. The Oracle wireless node’s main processor is an Atmel AT91RM9200 system on a chip which is based on an ARM (Acorn Reduced instruction set computer Machine) processor which has 512 K of RAM and 4 MB of flash memory. The sensor communication board design is based on the IEEE 802.15.4 radio over the 2.4 GHz frequency band (Oracle Corporation 2012).

Fig. 4 Oracle Sun Spot wireless sensor (Photos from Gokhan Kilic 2012)

Fig. 5 Diagram of the system (Photos from Gokhan Kilic 2012)

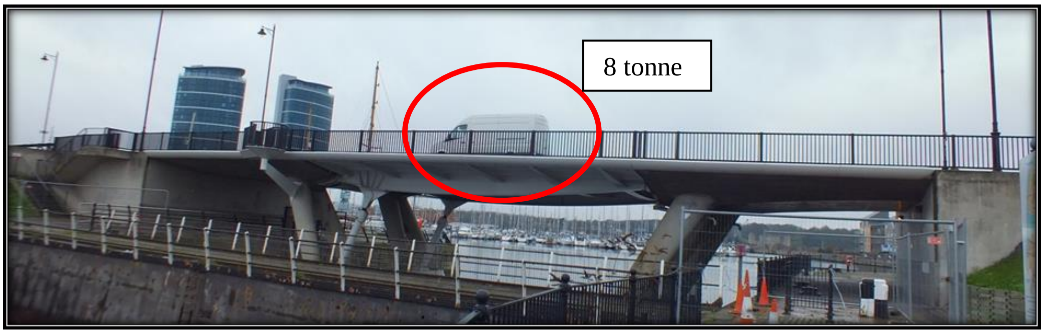

Fig. 6 The vehicle passing the bridge while data acquisition (Photos from Gokhan Kilic 2012)

2.4 Monitoring strategy of HMS Chatham Bridge

The WSN tests were carried out on 11 June 2012. The weather was dry and sunny and the temperature was 16°C. It was necessary to introduce a traffic control system on the day as the bridge is heavily used by members of the public. The aim of this experimental study, as discussed previously, was to obtain deflection results using the two protocols for WSN, which could then be compared. Accelerometers were also positioned on the bridge to provide results which could be used to validate the findings of the WSN (see Fig. 10).

Fig. 5 shows the locations of wireless sensor nodes (W), the laptop and base station. The wireless sensor system implemented included a base station and eight wireless sensor nodes which communicated with each other, collected data and transmitted it to a base station via a radio link. The base station was connected to a laptop via USB port and interfaced the wireless sensor nodes and a host, which then gathered coordinate data.

In order to simulate dynamic loading an 8 tonne vehicle (extra load was weighted before testing) was driven across the bridge 16 times during each acquisition period. This monitoring ensured that the vehicle was moving at an almost constant speed to prove the repeatability of this survey (Fig. 6).

Table 2 shows how two different protocols (AODV and DSR) were used, eight times each, and a measurement of the approximate crossing duration was recorded. The speed of the vehicle remained constant at 25MPH which was confirmed using the speedometer.

Table 2 Moving load crossing time

	AODV (second)	DSR (second)	
1	6.16	6.12	
2	6.53	6.23	
3	6.43	6.54	
4	6.17	6.29	
5	6.25	6.35	
6	6.28	6.29	
7	6.57	6.10	
8	6.53	6.48	
Average	6.36	6.30	6.33

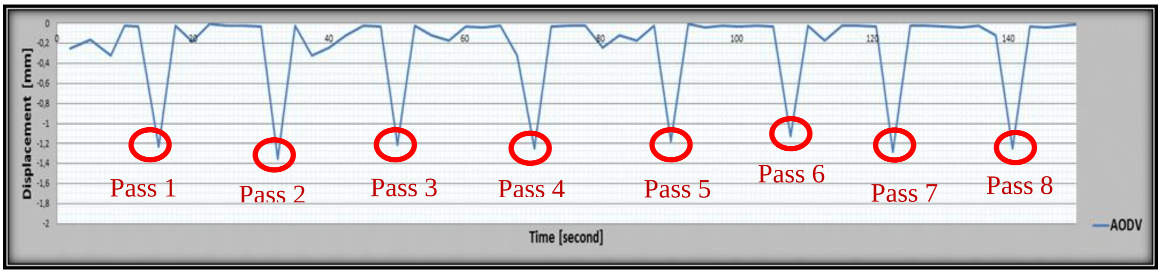

Fig. 7 Deflection time history diagram at the WSN node 1 (AODV)

3. Results

When a load is applied to the deck, usually in the form of a vehicle, the nodes are able to measure the deflection of the deck displacement. By repeating the test with the deck loaded and unloaded comparisons between the 16 sets of data can be made and the structure's behaviour under load can be assessed. It is possible to assess the structure under dynamic, live and static loads.

One of the disadvantages discovered during the survey related to WSN was the energy efficiency and power supply problem. The wireless sensor nodes were battery-powered and re-charged by using cables connected to a laptop. Each complete set of moving load movements took approximately 10-15 minutes to complete (a set comprised of 16 bridge crosses), during which time the wireless sensors often ran out of battery power and needed to be charged. During the survey the solution to this problem was to minimize the power consumption of the wireless sensor nodes, for example by switching off the nodes during waiting times.

Fig. 7 provides an example of the first eight passes of the 8 tonne vehicle which shows the deflection time history from WSN node 1 during the duration of the survey. Each of these passes is clearly shown by the maximum deflection being achieved at four separate points. This can be validated as the timing of the survey is also recorded, and at each point of maximum deflection it is visually confirmed that the moving load is present at that position of the bridge structure.

The purpose of this paper is to compare the AODV and DSR protocol results and to understand how structures perform under moving load conditions. It was found that both protocols provided very similar results for the deflection of bridge deck. Fig. 8 illustrates the deflection at node 1 of the bridge over time for both AODV and DSR protocol results. As can be clearly seen, when the

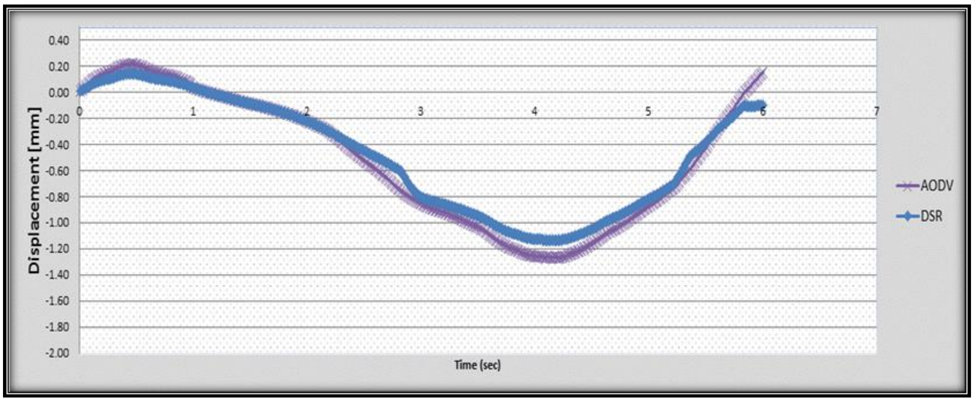

Fig. 8 AODV and DSR WSN results

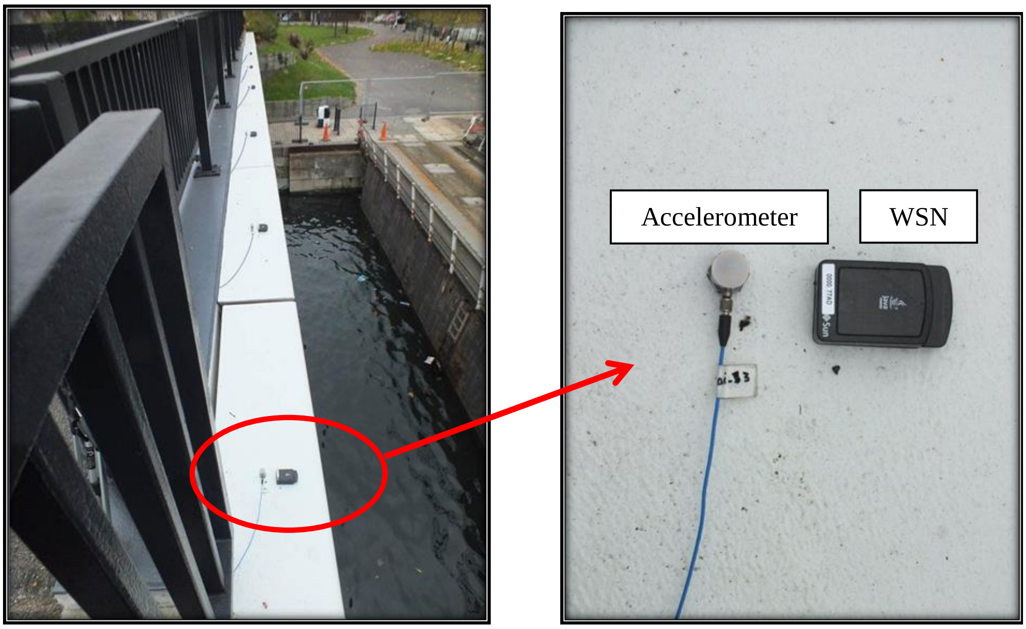

Fig. 9 Wireless Sensor Node and Accelerometer Sensor (Photos from Gokhan Kilic 2012)

load is located on this node the maximum displacement for both methods is seen. It has also been observed that good correlation between the results is seen at all other times.

3.1 Validation of WSN

Accelerometer sensor results were obtained for the bridge's deflection in order to validate the WSN results and to provide additional confidence in their measurements.

Accelerometers are rugged, stainless steel vibration monitoring sensors for predictive maintenance applications. They are hermetically sealed and case isolated. Also accelerometer sensors interface directly with handheld data collectors for both permanent mount and route based applications (PCB Group 2012).

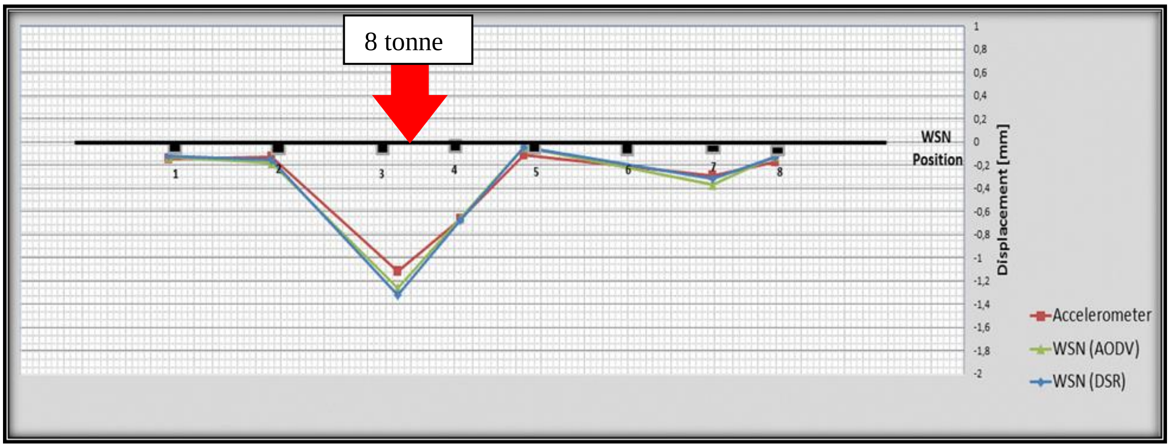

Fig. 10 Validation results

Fig. 9 shows a wireless sensor node and Accelerometer sensor installed to one side of HMS Chatham Bridge.

Fig. 10 shows displacement results for the WSN and accelerometers for several passes of the 8 tonne vehicle.

There is no significant difference between the measurements from the WSN and accelerometer sensors. This satisfactorily validates the WSN and allows for further analysis.

The insignificant discrepancy seen between the results could be owing to several different causes such as: the difference in horizontal positioning of the sensors and completely different methods of calculating displacement.

In conclusion, as is seen from the figures detailed in the results section, the accelerometer deflection measurements have successfully validated the WSN findings (Fig. 10). There are some minor discrepancies between the data but this can be attributed to the causes listed above.

3.2 Simulation and comparison AODV and DSR routing protocols

The protocols were compared on a number of key criteria: battery life, end-to-end delay and network load. The battery life has been measured during the actual case study of deflection whereas end-to-end delay and network load were simulated using OPNET software.

3.2.1 Battery life

It is crucial to optimize the battery life of WSN sensors as often in field conditions such as the monitoring of bridge deflection, it may be impossible to charge the devices. Also if the battery consumption is minimized it may be possible to utilize solar power or another natural source.

In this study, in order to conserve battery life, the WSN nodes were programmed to change their status to sleep mode when they are not sensing data.

Battery level readings for DSR and AODV are compared at Fig. 11, from which it can be seen that DSR discharges power more quickly than AODV. Different nodes discharge different power levels which results in plateaus and steep drops but also battery levels can be affected (to a lesser degree) by such events as blinking LEDs on the sensors. For these reasons, it could be argued that AODV is more appropriate for bridge health monitoring.

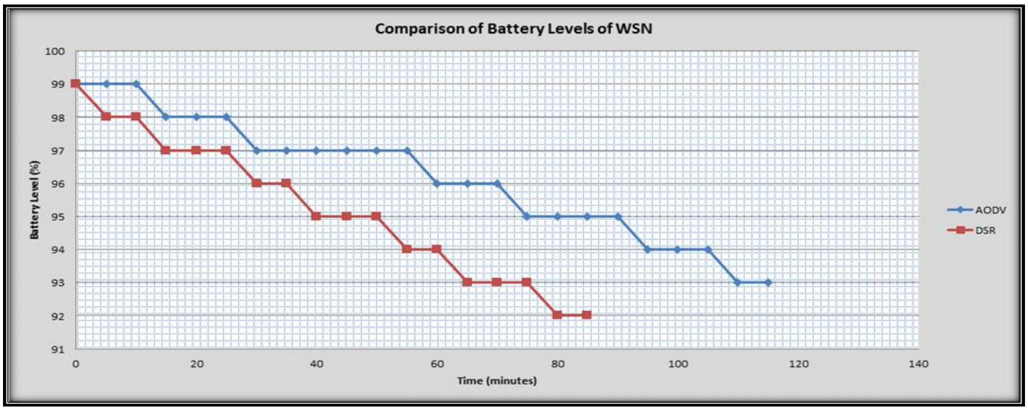

Fig. 11 Comparison of battery levels of WSN nodes in the case study

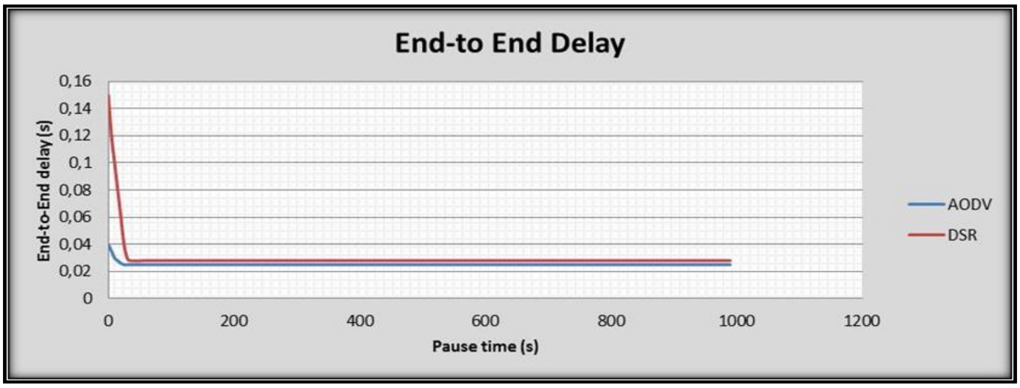

Fig. 12 End-to-End Delay comparison between DSR and AODV

3.2.2 End-to-End delay

End-to-End Delay is a measure of the delay in receiving a signal between two nodes, this can lead to inaccurate measurements of deflection and thus is important to minimize.

Fig. 12 illustrates how, during the simulation, the DSR routing protocol experienced a higher end-to-end delay than that experienced for AODV. An explanation for this was that the cache memory of the DSR routing protocol delayed forwarding data to the routing layer for 0.1522 seconds at a pause time of 100sec, while AODV delayed for just 0.034 seconds for the same pause time. However, upon increased mobility, a significant reduction in end-to-end delay to just 0.02 seconds (an 86.8% decrease) was seen for the DSR routing protocol whilst a slightly reduced end-to-end delay to 0.017 seconds was seen for AODV (a 68.5% decrease). Both protocols maintained route and link consistency at a steady flow in their end-to-end delay. The findings were explained by the pathway discovery process that takes place initially by both routing protocols leading to an increase in delay time, followed by a stabilising of the routing which results in decreased delay.

3.2.3 Network load

Network loading is the measurement of the quantity of data being transferred to the base station. A higher loading may result in increased accuracy but may diminish battery life.

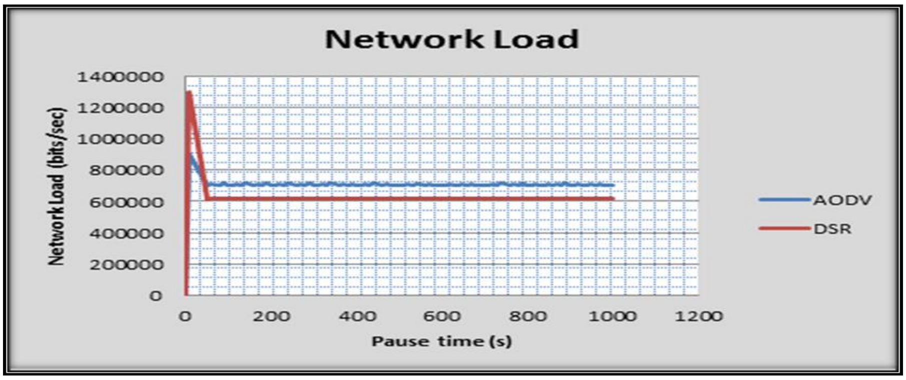

Fig. 13 Network load comparison between DSR and AODV

Network loading of AODV and DSR protocols are compared in Fig. 13. AODV has the higher network load of 1300 kbit/sec and DSR has a network load of 800 kbit/sec. Over the course of the simulation, the network load of AODV decreased significantly to about 600 kbit/sec while the DSR network load stayed at a regular 800 kbits/sec. The unsteady network load of AODV was explained by the steady stream of data being generated. The DSR protocol was shown to maintain a constant load during network load simulation whereas a 75% drop in routing load was witnessed for AODV. 99% and 98% confidence intervals were achieved for AODV and DRS routing protocols.

4. Discussion

The protocols discussed in this paper were selected as these are the most commonly used by WSN. The aim of this research was to evaluate them in terms of factors which impact on the performance, power consumption and accuracy of WSN as applied to bridge health monitoring. It was found that the AODV protocol was more beneficial for longer term simulations as it resulted in a longer battery life. However it did not show significant advantages with regard to the other parameters measured: network loading and end-to-end delay. This is an important finding as the battery-life measurements were taken during an actual survey whereas previous literature was based solely on simulations.

The findings of this paper are similar to literature which demonstrates the small advantages of the AODV protocol. With respect to data transfer this is shown by Fig. 13 which illustrates the network load of each protocol. It is clear that the AODV protocol performs consistently faster than the DSR. It also experiences a lower end-to-end delay shown by Fig. 12. In theory this should result in a more accurate result for bridge deflection; however this was shown not to be the case in Fig. 7.

The major significance of these findings is the proof that the AODV protocol is as accurate as other protocols (DSR) but utilises less battery life. This has been successfully monitored in a field study environment; previously this finding has been purely theoretical.

It is therefore recommended that the AODV protocol be used when embedded monitoring is required and further studies should be completed to examine long-term simulations using it. These findings could positively impact on survey plans, enabling longer field monitoring of structures as less recharging is needed. Also, by coupling the WSN with solar power and a limited power consuming protocol such as AODV, long-term continuous simulation is also a possibility. Both of these scenarios would allow for more data to be acquired giving a more comprehensive view of structural behaviour. The installation of long term sensors would also decrease the disruption caused by continually installing and removing sensors for short-term monitoring. It is intended that additional research should be undertaken to refine WSN protocols to decrease power consumption further, potentially investigating a bespoke protocol targeting bridge health monitoring. This would ensure that it is viable to couple it with solar power sources, thus increasing the likelihood of continuous long term monitoring, as discussed above. This could be utilised by developing countries when monitoring bridges as other power sources may not be readily available. Bridges in developing countries are more prone to collapse due to their construction and it would thus be of major importance to develop long term monitoring on these structures using solar power (Zhu *et al*. 2010).

5. Conclusions

In this paper, two WSN protocols (AODV and DSR) were evaluated in terms of accuracy and battery life using a case study and network loading and end-to-end delay using OPNET simulations. The case study consisted of bridge deflection monitoring on HMS Chatham Bridge.

It is important to select the correct WSN protocol as this determines the applicability of wireless sensor nodes for bridge health monitoring. In previous research it was indicated that an Ad-Hoc on demand distance vector (AODV) routing protocol approach yields significantly better results than dynamic source routing (DSR) protocol and this was affirmed by OPNET simulations performed on HMS Chatham Bridge. However previous recommendations were purely based on theoretical results of computer models and no real world data was available to compare their results.

This paper provides this data, thus giving a greater understanding of protocol selection and further knowledge of applying these protocols in the field. In this paper it was shown that the AODV had a higher network load and lower end-to-end delay which in theory should result in more accurate deflection results. However when this was compared to the actual deflection, no significant difference in accuracy between the two protocols was seen. In terms of battery life, the AODV routing protocol is still more beneficial in the field as it has a longer battery life enabling longer surveying times. This is a significant finding as it was deemed that the SunSPOT WSN are inappropriate for long term bridge health monitoring, owing primarily to their short battery life.

If protocols which optimise battery life such as the AODV routing protocol are utilized it may be possible in the future to couple WSN with, for example solar power, in order to prolong their monitoring periods. This would considerably decrease the cost of structural response measurements as WSN are more cost effective than other methods such as Accelerometer sensor monitoring, resulting in a greater pool of results of bridge deflection and therefore an increase in data that can be used for health monitoring.

Acknowledgements

The author wishes to acknowledge for the important suggestions and extensive review on the paper made by Luc Tidy and Ruth Quinn from University of Greenwich and important contributions made by anonymous reviewers on the initial manuscript.

References

Basharat, A., Catbas, N. and Shah, M. (2005), "A framework for intelligent sensor network with video camera for structural health monitoring of bridges", *Pervasive Computing and Communications Workshops, PerCom 2005 Workshops, Third IEEE International Conference*, March.

Bello, L., Bakalis, P., Manam, S.J., Eneh, T.I. and Anang, K.A. (2011), "Power control and performance comparison of AODV and DSR ad hoc routing protocols", *UKSim 13th International Conference on Modelling and Simulation*.

Chae, M.J., Yoo, H.S., Kim, J.Y. and Cho, M.Y. (2012), "Development of a wireless sensor network system for suspension bridge health monitoring", *Automation in Construction*, **21**, 237-252.

Chang, Z., Gaydadjiev, G. and Vassiliadis, S. (2005), "Routing protocols for mobile ad hoc networks: Current development and evaluation", *IEEE Comput. Soc*., 187-194.

Chatham Maritime House (2010), http://www.cmtrust.co.uk.

Culler, D. and Hong, W. (2004), "Wireless sensor networks", Communications of the ACM, **47**, 30-33.

Dwivedi, D., Dubey, S., Verma, A. and Lala, A. (2012), "Energy efficient reactive routing using energy evaluation model with CBR and VBR traffic model", *Int. J. Elec. Comput. Sci. Eng.*, **1**(4), 2368-2376.

Farhey, D. (2006), "Integrated virtual instrumentation and wireless monitoring for infrastructure diagnostics", *Struct. Hlth. Monit*., **5**, 29-43.

GUOA (2011), "Optimal sensor placement in structural health monitoring (shm) with a field application on arc bridge", University of New Mexico, USA.

Pirzada, A. A., Portmann, M. and Indulska, J. (2006), "Performance comparison of multi-path aodv and dsr protocols in hybrid mesh networks", *Networks, ICON '06. 14th IEEE International Conference*, September.

Kamel, G. (2010), "Energy efficient structural health monitoring of the cutty sark using wireless sensors".

Kim, J. and Lynch, J.P. (2012), "Experimental analysis of vehicle bridge interaction using a wireless monitoring system and a two stage system identification technique", *Mech. Syst. Signal Proc*., **28**, 3-19.

Kim, J.T., Ho, D.D., Nguyen, K.D., Hong, D.S., Shin, S.W., Yun, C.B. and Shinozuka, N. (2013), "System identification of a cable-stayed bridge using vibration responses measured by a wireless sensor network", *Smart Struct. Syst*., **11**(5), 533-553.

Lee, R.G., Chen, K.C., Lai, C.C., Chiang, S.S., Liu, H.S. and Wei, M.S. (2007), "A backup routing with wireless sensor network for bridge monitoring system", *Measurement*, **40**, 55-63.

Oracle Corporation (2012), Sun Spot LIMITED. http://www.sunspotworld.com.

PCB Group (2012), http://www.pcb.com.

Sun Oracle (2011), Sun™ SPOT Programmer's Manual, Release v6.0. Sun Labs, November. http://www.sunspotworld.com/docs/Yellow/SunSPOT-Programmers-Manual.pdf.

Walker, R. (2010), "Issues current UK bridges", *Seminar on Assessment and Maintenance of Concrete Highway Bridges*, UK, April.

Whelan, M.J., Gangone, M.V. and Janoyan, K.D. (2009), "Highway bridge assessment using an adaptive real-time wireless sensor network", *Sensors J., IEEE*, **9**, 1405-1413.

Zhu, Z., German, S. and Brilakis, I. (2010), "Detection of large-scale concrete columns for automated bridge inspection", *Automat. Constr*., **19**, 1047-1055.