Cost Benefit Analysis of Utilising Mobile Nodes in Wireless Sensor Networks

Mathur, Prateek; Nielsen, Rasmus Hjorth; Prasad, Neeli R.; Prasad, Ramjee

Published in:
Wireless Personal Communications

DOI (link to publication from Publisher):
10.1007/s11277-015-2529-5

Publication date:
2015

Document Version
Accepted author manuscript, peer reviewed version

Noname manuscript No.
(will be inserted by the editor)

Cost Benefit Analysis of Utilising Mobile Nodes in Wireless Sensor Networks

**Prateek Mathur · Rasmus H. Nielsen ·
Neeli R. Prasad · Ramjee Prasad**

Received: date / Accepted: date

Abstract Mobile nodes have been found useful for improving performance of network parameters such as coverage, data latency and load balancing in wireless sensor networks (WSNs). In spite of the benefits which mobile nodes could offer when used in WSNs, they have been often stated as infeasible for use. As they are expensive compared to static nodes in terms of manufacturing and mobility cost. This paper evaluates the utility of mobile nodes for use in WSNs in comparison with static nodes. Novel geometric models to represent the various functionalities for which mobile could be used have been proposed, they have been utilised for the techno-economic evaluation based on cost benefit analysis. The models have been designed such that they give a generic representation of the functionalities, and enable a fair comparison between them. On the basis of the analysis it is concluded that apart from the functional utility, mobile nodes are economically beneficial for use in WSNs.

Keywords cost benefit analysis · techno-economic modelling · mobile nodes · wireless sensor networks · geometric model

1 Introduction

Wireless sensor networks (WSNs) can either be deployed in a deterministic or random manner. Deterministic deployment of WSNs is feasible if the area of interest (AoI) is small. However, in many of the envisioned applications for

Prateek Mathur · Neeli R. Prasad · Ramjee Prasad
Center for TeleInFrastruktur, Department of Electronic Systems
Aalborg University, Aalborg 9220, Denmark
E-mail: [in_pm, np, prasad]@es.aau.dk

Rasmus H.Nielsen
Cisco Systems, San Jose, USA
E-mail: rhnielsen@ieee.org

WSNs, random deployment of sensor nodes in the AoI would be necessitated. Especially if the AoI is large and aerial (remote) deployment is necessitated. Random deployment of sensor nodes would result in some nodes to overlap and clump together while some of the other would be sparsely located [1]. Improving the coverage in a random deployment is feasible by using more nodes than the minimum required to fill the area, or relocating the mobile nodes within the AoI. Use of mobile nodes can be avoided completely if static nodes can be deployed in much larger number than the minimum required for covering a certain AoI. This would only be possible when bulk production of static nodes would be economically viable. Mobile nodes have been found useful for improving coverage of all types (area, barrier and target coverage) [2], [3], [4], and are also used for load balancing the data traffic in the network functioning as mobile relay, mobile base station (BS) and data mule [5], [6]. Throughout this paper, we refer the use of the mobile nodes for aforesaid purposes as their *functionalities* in WSNs. WSNs are energy constrained since the battery power usually cannot be replenished after exhaustion due to the infeasibility imposed by deployment in hostile conditions and / or large AoI. Mobile nodes cost more than static nodes and the movement of nodes (actuation) consumes significant amount of energy, manifold higher than the other energy intensive operation of radio communication between the sensor nodes. Therefore, their use for aforesaid functionalities requires proper planning. Mechanisms to use mobile sensor nodes efficiently for various functionalities, in a manner such that the movement cost of nodes is minimal, have been covered extensively in the literature. On the other hand, their likely acceptance is doubted by many. In this paper we are evaluating the utility of mobile nodes compared with static nodes based on cost benefit analysis. Novel geometric models to represent the functionalities performed by mobile nodes in the network have been proposed. Operational cost comprising of movement cost and information exchange (communication overhead) carried out by mobile node with other nodes for coordinating the navigation have been derived based on these models. A mobile node could perform a certain functionality multiple times over its lifetime, accordingly, a single instance of this is defined as a functionality round (FR). The remaining paper is structured as follows: Section 2 highlights the related work; and Section 3 presents the background on techno-economic modelling, and cost benefit analysis. In Section 4 the proposed geometric models to represent the various functionalities have been presented, and procedure for determining the operational cost for accomplishing the functionalities. In section 5, the overall cost benefit analysis of utilising mobile nodes in wireless sensor networks is presented, and this paper is concluded in section 6.

2 Related Work

Various coverage improvement mechanisms for WSNs based on relocation of mobile nodes have been discussed in [3]. The mechanisms are classified into three broad categories which are: coverage pattern, virtual force and grid quorum based node movement. The influence of mobile node density on target detection in WSNs with respect to the detection latency and mean first contact distance with target have been analysed in [4]. The authors also analysed the difference in performance based on the fraction of total nodes considered as mobile. Similarly, the utility of mobile nodes for creation of barrier coverage has been discussed in [7]. Utility of mobile relays for transferring data intensive information in WSNs has been presented in [5]. In [8], the authors propose an over-positioning metric to indicate the efficiency of a network deployment strategy and the amount of static nodes that are required to be over-positioned compared with a hybrid deployment (static + mobile nodes). Mobile node platforms such as Robomote, CotsBots, Racemote, Millibots, Khepera [9, 10] have been developed by researchers, designed for mobility within the network. These mobile nodes rely on mobility mechanism (actuation) in form of motor driven wheels.

Even though use of mobile nodes for the various possible functionalities stated earlier has been evaluated extensively in the literature. To the best of authors' knowledge there has been no work in which mobile nodes have been evaluated for their utility in WSNs on a techno-economic basis, or even the utility of deploying WSNs per se in economic terms. Economic evaluation in other area of wireless communication such as access networks has been carried out [11]. Techno-economic evaluation of access networks technologies for FiWi networks comparing between WiMax and EPON has been presented in [12]. Techno-economic aspects concerning cognitive radio regulatory and policy aspects has been presented in [13]. Also, there is no existing work that describes the communication cost or the distance the mobile node has to cover in order to accomplish a certain functionality in the generic form. This is the first work where various possible functionalities of the mobile nodes in WSNs have been compared. Based on overall operational cost to accomplish them represented in monetary terms, derived utilizing novel geometric models.

3 Background Techno-Economic Modelling

Techno-economic modelling involves examining technology feasibility, and cost analysis for economic viability of a technology. The economic competitiveness of a technology is assessed by evaluating its implementation costs for a given process compared to the costs incurred by current technology. Tools used for technology feasibility analysis include process modelling, equipment cost modelling, cost benefit analysis and cash flow analysis [14]. In this paper the usability of the mobile sensor nodes is compared with static nodes for various functionalities based on cost benefit analysis (CBA).

Cost benefit analysis is utilised for determining the outcome of a program or process by expressing the applicable cost and likely benefit to be garnered represented in monetary terms [15]. As stated earlier, we are evaluating use of the mobile nodes in the network compared with static nodes based on possibility of utilising them for a certain functionality. Intuitively the benefit of using a mobile node would be the number of static nodes that match the functionality capacity of a single mobile node. In our evaluation, the CBA consists of capital cost (CAPEX) in the form of manufacturing cost of the mobile nodes, and operational cost (OPEX) comprises implied cost of navigation and communication overhead for coordinating the movement of the mobile node. In a remote deployment, cost of installation of the network would not matter whether the deployed nodes are static or mobile. Similarly, the cost for collecting the nodes after deployment objective is accomplished, and the environmental damage likely to result because of the network deployment. Inclusion of these costs would be suggestible future work in determining the overall economic feasibility of WSNs.

4 Proposed Method

The geometric models to represent the various functionalities of mobile nodes are elaborated in this section, along-with applicable cost for accomplishing the various functionalities based on geometric models. The difference between static and mobile nodes in operational capacity is also discussed in a separate subsection.

4.1 Geometric Model

The cost of performing the functionality by the mobile node would depend on the distance the mobile node has to move, and the information exchange that it has to carry out with other nodes in the AoI for navigating to the destination. Various functionalities that the mobile node could accomplish in WSNs can be represented by geometric models. The area of the geometric model (referred to as *functionality area* from here on), would be utilised to determine the distance mobile node has to cover to accomplish the functionality. In order to accomplish the functionality, mobile node is required to relocate on any point in the functionality area, including the perimeter of the functionality area. Intuitively, communication cost would be inversely related with the functionality area, considering the fact that it would be harder to relocate into a small area compared with a large area, this is defined as *complexity factor*. The total communication cost defined as *complexity cost* is derived based on the complexity factor. Calculation of distance and complexity cost has been discussed in subsections 4.7, 4.8 and 4.9 respectively.

The geometric models shown for the functionality have not be drawn to scale. The distance derived based on the geometric models would differ with distance derived from a simulated evaluation of the mobile node movement for any of the functionality. Since, in the latter the distance is determined based on calculation of shortest distance between two points and averaged across multiple executions of the simulation. It is considered for this techno-economic evaluation that mobile nodes would have access to some path guiding with help of waypoints (communication cost) and amount of randomness in movement of mobile nodes is not very significant, as would be applicable under random mobility model. The mobile nodes do not have access to localization service such as global positioning service (GPS). The influence of deployment conditions in regard to deployment surface (undulating or levelled) and possible hindrance/obstacles in path of mobile nodes have not been considered as it is not possible to model them through a generalised geometric model. As this would involve a three dimensional non uniform operational space. However, it can be safely assumed that the functional difference between mobile and static node would scale in a similar proportion as existent between them in a two dimensional evaluation.

The possible functionalities of mobile nodes in WSNs are considered here and include: area, target, barrier coverage, and mobile relay / BS. Mobile target coverage is the only possible functionality apart from aforesaid functionalities for mobile nodes in WSNs. This functionality has not been considered here, as it is infeasible to represent this functionality through a geometric model. The derivation of the geometric models for the four functionalities are discussed in individual subsections later.

4.2 Benefit of Using Mobile Nodes

Benefit of a mobile node in the network would be the number of static nodes (over-positioning) that would match its functionality. The authors of paper [8] have derived the density of static nodes that are needed to guarantee the k-coverage, as per the following equations:

$$\lambda = \log \ell^2 + (k+2) \log \log \ell^2 + c(\ell) \tag{1}$$

$$c(\ell) \to +\infty \qquad as \qquad \ell \to +\infty \tag{2}$$

$$c(\ell) = o(\log \ell^2) \tag{3}$$

In the case of a hybrid network deployment (static + mobile nodes) the density of the nodes would be:

$$\lambda = 2\pi k + \sqrt{2\pi k} \tag{4}$$

Therefore, the amount of additional static nodes required if there are no mobile node(s) would be the difference of (1) and (4). Equation (3) would hold true for all positive value for constant ε, as the applicable condition of little o - notation, here it is considered as 1. Length (ℓ) represents the length of AoI. For the analysis ℓ is considered to be 100 and k as 1 (minimal full coverage of the AoI). The difference in density (λ) requirement as derived is $5.4 \simeq 5$. This has also be substantiated based on a simulated comparison of the nodes to attain full coverage when all nodes can move (network with only mobile nodes) unconditionally and for an all static node random deployment. The number of nodes required are 100 and 480 respectively, *i.e* $\approx$ 1:5 has been stated in [16]. Therefore, one mobile node is equal to five static nodes in terms

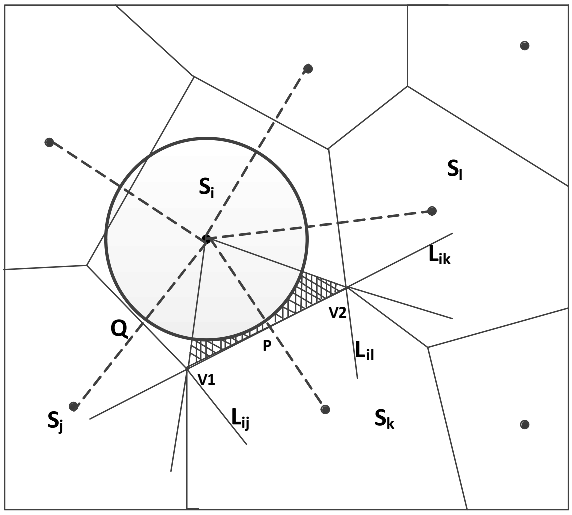

Fig. 1 Voronoi diagram for determination of coverage hole [3]

of its functional capacity (utility). This functional capacity difference between the mobile and static is used in for the techno-economic evaluation in this paper. Cost of performing a FR is determined for the functionalities based on geometric models in the following subsections.

4.3 Area Coverage

Area coverage describes how well the AoI is covered collectively by all the sensor nodes. Mobile nodes can relocate to fill a coverage hole anywhere in the AoI. Coverage hole is described as a region which is not under the sensing radius of any sensor node [2],[3]. Coverage holes can be determined based on Voronoi diagrams. A detailed procedure to determine a coverage hole has been presented in [2] and it has been elaborated here. Determination of the coverage hole is based on a network deployment situation as illustrated in Fig. 1. The shaded region is a coverage hole. The area of this coverage hole is determined as follows:

$$\text{Coverage hole area}(S_i) = \frac{l_{ik} d(s_i, s_k)}{4} - \frac{x_{ik} R_s^2}{2} \tag{5}$$

Where l_{ik} is related with line segment V_1 and V_2 to be derived by solving equations of L_{ik}, L_{ij} and L_{il} that are perpendicular lines connecting S_i, S_k, S_j and S_l (sensor nodes) respectively. x_{ik} is determined by cosine rule once aforesaid line equations are determined and $d(s_i, s_k)$ can be safely assumed to be equal to the communication distance between the sensor nodes. Since the line equations cannot be determined unless all the deployment details are known, the coverage hole area cannot be calculated using (5). It is stated

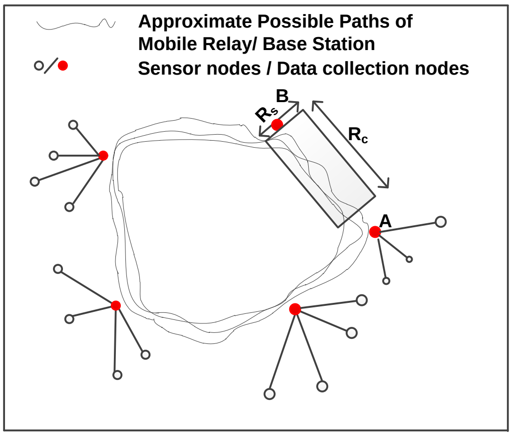

Fig. 2 Mobile relay / BS collection path in AoI

in [2] and [3], that mobile node relocation should take place when the size of coverage hole is larger than a threshold given by $\rho\pi R_s^2$ $(0 < \rho \leq 1)$. Therefore the functionality area is considered as 75 m^2 for area coverage with $\rho = 1$ (max) and sensing radius R_s as 5 m. The same value for sensing radius is used throughout rest of the paper, communication radius R_c is considered as $2R_s$ *i.e.* 10 m.

4.4 Mobile Relay / Mobile Base Station - Data Mule

This functionality of the mobile node is intended to help specific node(s) in the network by reducing the total packets transmitted in a multi-hop manner. It requires the mobile node to be within communication radius of the node(s) from which it has to collect the packets or assist in relaying packets. As stated earlier the functionality area is described as the region, such that if the mobile node is somewhere on the region it will accomplish the functionality. A sample layout of the mobile node expected path for this functionality is shown in Fig. 2. Based on the figure, if the mobile node has to collect data from node B (working as mobile BS / data mule) or it is assigned to assist node B in relaying (mobile relay), and the mobile node is approaching node B from node A, it can be safely assumed that traversing between the two nodes probable width would be $\leq R_s$ (deviation from shortest path joining the two nodes, only limited randomness). Therefore, if node (B) is in communication radius (R_c) of the mobile relay / BS, the functionality would be accomplished. There could be variation in the actual path undertaken by the mobile node as shown by the possible paths based on the availability of waypoints. The geometric

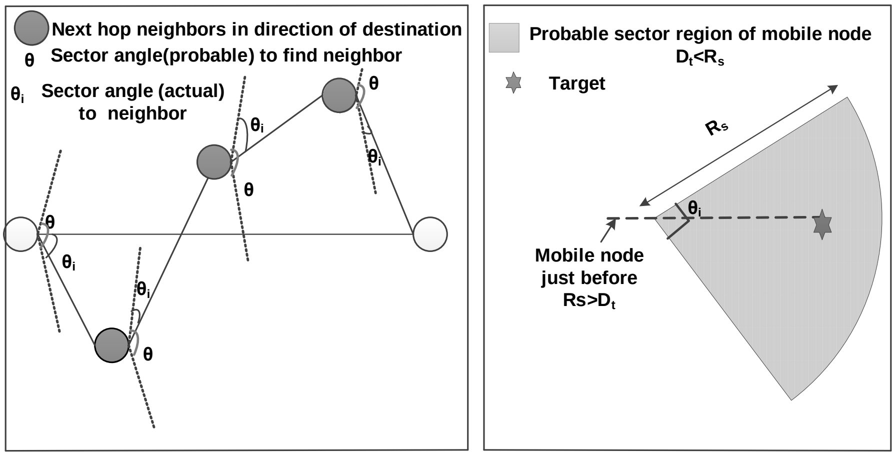

Fig. 3 a) Node looking for a neighbour towards the destination b) Geometric model for target coverage functionality

model to represent this functionality is a rectangle with the area:

$$R_c \times R_s = 50\, m^2 \tag{6}$$

4.5 Target Coverage

The authors in [17] state that when a node has to transmit information to a destination it will look for a neighbour in the destination direction within a sector region with angle θ, forming an actual angle θ_i (with the neighbour node) as shown in Fig. 3 a to get a multi-hop route to the destination. Here it is considered that the mobile node looks for the target in target coverage functionality in a similar sector region when the distance to target $(D_t) \leq R_s$, as shown in Fig. 3 b. The possible angle θ has been considered as $90°$ as that would be the maximum possible sector angle and functionality area is therefore:

$$\frac{\theta}{360}\pi R_s^2 = 19.62\, m^2 \tag{7}$$

4.6 Barrier Coverage

For barrier coverage functionality, the mobile node is required to relocate to fill in any gaps in the barrier to prevent the intruder from crossing a barrier region undetected, to ensure this the nodes are usually organised in multiple parallel layers. Barrier coverage with random deployment considering two layers can be illustrated as shown in Fig. 4 a. Possible route the intruder could take to escape undetected due to vacant space in the layers is also shown. It can be

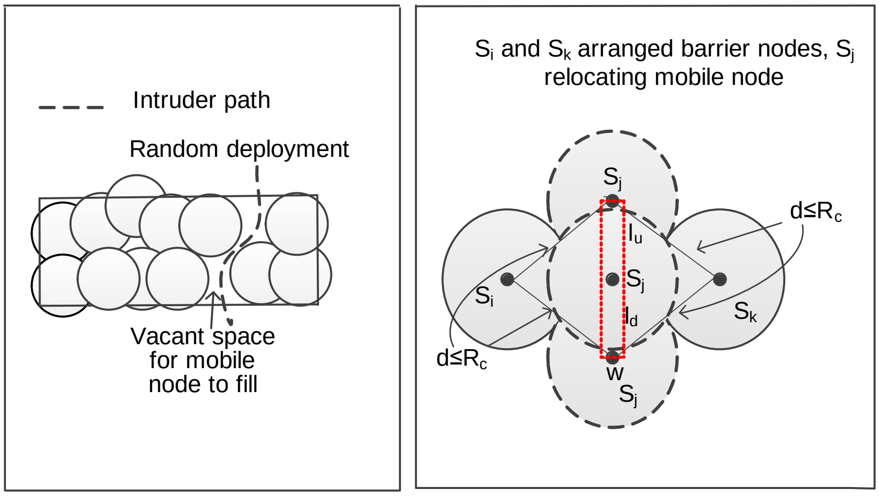

Fig. 4 a) Random deployment - barrier coverage b) Geometric model representing the functionality

observed that in the random deployment the nodes have to overlap to ensure barrier protection and the number of nodes required is higher compared with deterministic deployment. The functionality area is modelled as desirable area within which mobile node should relocate. As can be observed in Fig. 4 b, a node can move only to an extent in leftward or rightward (w) direction, and upward or downward (l_u and l_d) direction in reference to right and left neighbour nodes in the barrier region. The maximum movement in upward (l_u) and downward (l_d) direction will happen till the point mobile node is within the communication range of the neighbouring node *i.e.* R_c ($2R_s$). Considering that the mobile node can have a maximum overlap of 20% *i.e.* 1 m ($w = 1$ m) with left and right neighbours. The initial distance between the center of nodes is 4.75 m ($i.e < R_s$) and the overlap is 0.25 m, l_u is 8.8 m. The geometric model for barrier coverage functionality is a rectangle with the area:

$$(l_u + l_d) \times w = 17.60\, m^2 \tag{8}$$

4.7 Functionality Round (FR) - Distance

In the previous subsections, the functionality areas have been determined within which the mobile node should relocate (including the perimeter of the region). The various geometric models stacked on top of each other are shown in Fig. 5. To obtain an uniform comparison between the various functionalities, geometric models are redrawn with the area as determined earlier into concentric circles. With a common starting point for all the functionalities the distance applicable to accomplish any of functionality would be the distance needed to reach the circumference of the concentric circle representing

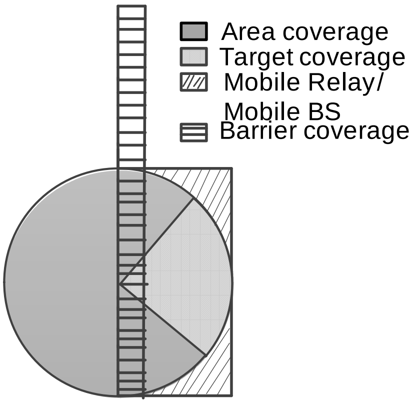

Fig. 5 Geometric model (actual) for various functionality stacked together

it, as shown in Fig. 6. Where the circles are considered centred at the center of the AoI ($100 \times 100\ m$). The distance of the starting point and the center of AoI is 70.71 m (Pythagoras Theorem), and therefore distance to reach the circumference of the functionality - area coverage is 70.71 m - 5 m = 65.71 m. The distance to reach the other functionality areas are determined adding the difference between the radius of the two circles. Therefore, the distances to reach the other three functionality areas: mobile relay / BS, target coverage and barrier coverage are 66.82 m, 68.31 m and 68.43 m respectively.

4.8 Functionality Round (FR) - Communication Overhead

Mobile node would require to exchange information with other nodes (waypoints) in the network for coordinating its movement to the functionality area. This is defined as *complexity factor*, which is inversely related with the functionality area, it is derived by the following expression:

$$\frac{1}{\text{functionality area}} \times \text{AoI} \tag{9}$$

Packet loss and latency that might incur due to relocation of mobile node are not considered in this evaluation. It is assumed that multi-hop data communication taking place in the network is not impacted while the mobile node is relocating and after the mobile node has relocated for accomplishing a certain functionality. In this current work it is considered that mobile nodes do not have access to localization services including GPS. As a further extension of this current work the communication overhead applicable considering precise cost applicable for localization and path guidance. Additionally, the impact on overall utility of mobile nodes if mobile nodes possess GPS could be evaluated. Functionality area, distance and complexity factor for the various functionalities are summarised in Table 1. Based on *complexity factor*, the *complexity* *cost* (communication overhead), that summarily indicates the total information exchange that would be required to accomplish a certain functionality, is given by (10) in the following subsection.

4.9 Energy Capacity and Cost

The battery capacity is considered as 2800 mAh with operating nominal voltage of 1.5 V based on common rating of alkaline AA battery, equivalent to 4.2 Wh or 15120 J. Considering that at least 20% capacity of the node would be utilised for carrying out other network management task *e.g.* clustering - cluster elections, the available capacity for node mobility to accomplish functionality is 12096 J. The power consumption for unit distance (m) in Joules is 4595.4, calculated based on battery specifications given for Robomote in [9], battery capacity of 345 mAh and nominal voltage as 3.7 V. It is stated that the Robomote moves 180 m on a full charged battery, and therefore the cost of moving 1 m in Joules is 25.53 J. Considering improvements in motor and wheel design for the mobile nodes, today this value would atleast reduce by 10% i.e. 22.97 J. A normalised rate for information communication is considered at 1 μ J per bit to take into account other indirect transmission cost consumed in the radio circuit of the sensor node (actual one bit T_X cost is less). Packet size of 128 bytes is considered, and to take into account both T_X and R_X, the overall value is multiplied by 2. The overall complexity cost is therefore given

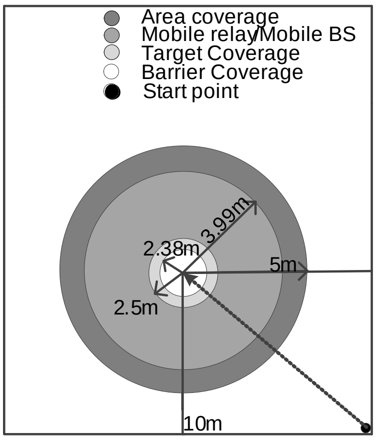

Fig. 6 Geometric models redrawn as concentric circles

Table 1 Functionality Details

Functionality	Area	Distance	Complexity Factor
Area coverage	75	65.71	133
Mobile relay/BS	50	66.82	200
Target coverage	19.63	68.31	509
Barrier coverage	17.60	68.43	568

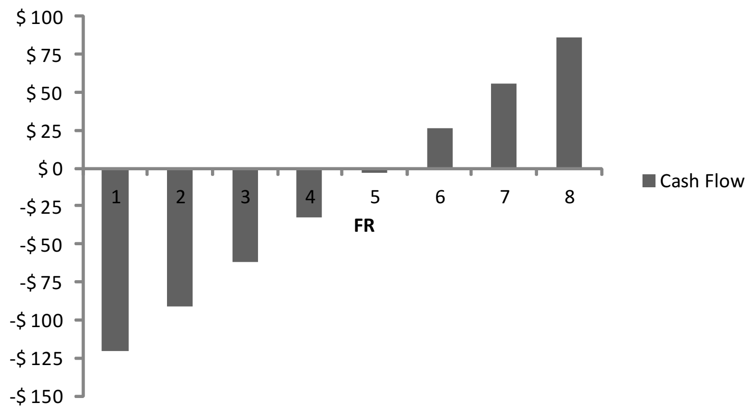

Fig. 7 Cash flow across the FRs - Area coverage

as follows:

$$\text{complexity factor} \times 128 \times 8 \times 1\mu J \times 2 \quad (10)$$

5 Cost Benefit Analysis

In the previous section, the implied cost based on the distance moved by the mobile node and that based on complexity of accomplishing the functionality have been derived. As derived earlier in subsection 4.2, one mobile node is equal to five static nodes. The cost of a static node is considered as $100 (based on Micaz mote cost given in [18] for 2009, to be applicable even today). This fact can be based on the observation that no new sensor node has emerged in market recently, especially a mobile node platform. Micaz is a popular and highly accepted sensor node and therefore its cost is considered for the evaluation in this paper. Cost of the mobile node is considered as $150 taking

Table 2 Summarised Cost Benefit Analysis for Various Functionalities

Specification / **Functionality type**	**Area Coverage**	**Mobile relay / BS**	**Target coverage**	**Barrier coverage**
Initial static node cost ($)	100	100	100	100
Additional mobile node cost ($)	50	50	50	50
Functionality cost (dist) (J)	1445.62	1470.02	1502.82	1505.46
Complexity cost (J)	0.27	0.40	1.04	1.16
Total functionality cost (J)	1445.89	1470.42	1503.86	1506.46
Cost (FR) ($)	14.31	14.55	14.88	14.91
Benefit (FR) ($)	43.75	43.75	43.75	43.75
Net benefit (1st FR)($)	-120.56	-120.8	-121.13	-121.16
Net benefit (end)($)	85.52	83.6	80.96	80.72

into account extra cost of peripherals and packaging. A mobile node would have extra peripherals for actuation (motor, wheels), and the overall sensor node would require additional packaging to accommodate the peripherals with the basic sensor node. The overall economic benefit of using a mobile node against static nodes is therefore 500 - 150 = \$350. Total benefit is incurred across the lifetime of the mobile node, benefit per FR would depend on the number of times the functionality can occur. Mobile node can perform this functionality 8 times (FRs), derived dividing the total energy capacity available with the mobile node by total FR cost in Joules. The cash flow for functionality - area coverage is shown in Fig. 7. Positive cash flow can be observed from the 6th round. Net benefit for the first FR and at the end of the lifetime for the various functionalities is shown in Table 2. The distance cost increases by 1.69%, 3.85% and 4.03% for mobile BS / relay, target coverage and barrier coverage compared with the area coverage. Similarly, the complexity cost in the same sequence with reference to area coverage area are 48.00%, 285.18% and 329.00% higher. The net benefit at the end of lifetime for area coverage and barrier coverage differ by \$4.8 ≈ \$5. The difference between net end benefit of the various functionality and their complexity factor, describes that various functionalities differ significantly. CBA also involves determination of the net present value (NPV) and NPV is determined by the following expression [15]:

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{11}$$

Where B_t and C_t represent benefit and cost for period, t, and n represents total number of benefits and costs in the project. For determination of NPV in the normal course, time period is considered in years, in the evaluation being undertaken definite time period cannot be determined. Time period is therefore considered as the number of FRs that can be performed, *i.e.*, $t = 8$ and discount rate i is considered as 5% as this is the most widely accepted discounted rate. Overall benefit, $B_t = 350$, and cost, $C_t = 114.48$, putting the values in (11), the NPV is 159.406. Positive value of NPV signifies that implementation of project / process is useful and vice versa implies for negative NPV [15], justifying the use of mobile nodes for performing the considered functionalities in WSNs.

6 Conclusions

Based on the evaluation it can be concluded that mobile nodes are economically beneficial for use in WSNs for various complex functionalities, under the modelling assumptions considered. Therefore, there is good opportunity for active manufacturing of mobile sensor nodes and this in turn could be useful for deploying large scale WSNs. Geometric models to represent various functionalities has been found to be effective to compare them in a generic manner, and in deriving the applicable cost of accomplishing them. Economic evaluation based on geometric modelling can be applied to compare and evaluate other aspects of WSNs. This paper justifies that techno-economic evaluation could be applied for possible applications and aspects that are usually considered infeasible to monetise. Additionally, an economic evaluation between the two node types considering the diffusion rate of sensor technologies and the manufacturing of inherent sensor node peripherals could be explored. The sensor node applications classified in form of basic functionalities is considered in this paper for the evaluation, this could be extended to model real applications.

References

1. R. Machado, W. Zhang, G. Wang, S. Tekinay, Coverage properties of clustered wireless sensor networks, ACM Trans. Sen. Netw. 7 (2010) 13:1–13:21. doi:10.1145/1824766.1824769.
   URL `http://doi.acm.org/10.1145/1824766.1824769`
2. A. Ghosh, Estimating coverage holes and enhancing coverage in mixed sensor networks, in: Local Computer Networks. 29th Annual IEEE International Conference on, 2004. doi:10.1109/LCN.2004.53.
3. B. Wang, H. B. Lim, D. Ma, A survey of movement strategies for improving network coverage in wireless sensor networks, Computer Communications 32 (13-14) (2009) 1427–1436. doi:10.1016/j.comcom.2009.05.004.
4. T. Wimalajeewa, S. K. Jayaweera, Impact of mobile node density on detection performance measures in a hybrid sensor network, Wireless Communications, IEEE Transactions on 9 (2010) 1760–1769. doi:10.1109/TWC.2010.05.091012.
5. F. El-Moukaddem, E. Torng, G. Xing, E. Torng, G. Xing, G. Xing, Mobile relay configuration in data-intensive wireless sensor networks, Mobile Computing, IEEE Transactions on 261–273doi:10.1109/TMC.2011.266.
6. G. Xing, M. Li, T. Wang, W. Jia, J. Huang, Efficient rendezvous algorithms for mobility-enabled wireless sensor networks, Mobile Computing, IEEE Transactions on 11 (1) (2012) 47 –60. doi:10.1109/TMC.2011.66.
7. A. Saipulla, B. Liu, G. Xing, X. Fu, J. Wang, Barrier coverage with sensors of limited mobility, in: Proceedings of the Eleventh ACM International Symposium on Mobile Ad Hoc Networking and Computing, 2010, pp. 201–210. doi:10.1145/1860093.1860121.
8. W. W. V. Srinivasan, K. C. Chua, Trade-offs between mobility and density for coverage in wireless sensor networks, in: Proceedings of the 13th annual ACM international conference on Mobile computing and networking, ACM, 2007, pp. 39–50.
9. K. Dantu, M. Rahimi, H. Shah, S. Babel, A. Dhariwal, G. Sukhatme, Robomote: enabling mobility in sensor networks, in: Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on, April, pp. 404–409. doi:10.1109/IPSN.2005.1440957.
10. G. Song, Y. Zhou, Z. Wei, A. Song, A smart node architecture for adding mobility to wireless sensor networks, Sensors and Actuators A: Physical (2008) 216 – 221doi:http://dx.doi.org/10.1016/j.sna.2008.05.005.
11. M. Kantor, K. Wajda, B. Lannoo, K. Casier, S. Verbrugge, M. Pickavet, L. Wosinska, J. Chen, A. Mitcsenkov, General framework for techno-economic analysis of next generation access networks, in: Transparent Optical Networks (ICTON), 2010 12th International Conference on, 2010. doi:10.1109/ICTON.2010.5549342.
12. N. Ghazisaidi, M. Maier, Fiber-wireless (fiwi) networks: A comparative techno-economic analysis of epon and wimax, in: Global Telecommunications Conference. GLOBECOM. IEEE, 2009.
13. K. Nolan, V. Gonalves, Economic aspects of CR policy and regulation, in: A. Medeisis, O. Holland (Eds.), Cognitive Radio Policy and Regulation, Signals and Communication Technology, Springer International Publishing, 2014, pp. 177–250.
14. T. Smura, Techno-economic modelling of wireless network and industry architectures, Ph.D. thesis, Aalto University School of Electrical Engineering (2012).

15. D. Greenberg, A. Vining, D. Weimer, A. Boardman, Cost Benefit Analysis: Concepts and Practice, Prentice-Hall, 2005.
16. P. Mathur, R. H. Nielsen, N. Prasad, R. Prasad, Coverage improvement for wireless sensor networks using grid quorum based node mobility, in: Networking and Electronic Commerce Research Conference, American Telecommunications Systems Management Association, 2012.
17. S. Panichpapiboon, G. Ferrari, O. K. Tonguz, Optimal transmit power in wireless sensor networks, EEE Transactions on Mobile Computing 5 (10) (2006) 1432–1447.
18. M. Johnson, M. Healy, P. van de Ven, M. Hayes, J. Nelson, T. Newe, E. Lewis, A comparative review of wireless sensor network mote technologies, in: Sensors, 2009 IEEE, Oct., pp. 1439–1442. doi:10.1109/ICSENS.2009.5398442.