This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2010 proceedings.

Impact of Power Control on Relay Load Balancing in Wireless Sensor Networks

Parth H. Pathak, Rudra Dutta
Department of Computer Science, North Carolina State University, Raleigh, NC, USA
Email: phpathak@ncsu.edu, dutta@csc.ncsu.edu

***Abstract*—When shortest path routing is employed in large scale multi-hop wireless networks, nodes located near the center of the network have to perform disproportional amount of relaying for others. In energy-constrained networks like sensor, such unfair forwarding results into early depletion of batteries of these congested nodes. To solve the problem, various divergent routing schemes are used which route the data on center-avoiding divergent routing paths. Though they achieve better load balancing, overall relaying is increased significantly due to their longer routing paths which in turn results into reduced energy efficiency. We propose power control as a way of achieving better load balancing in multi-hop wireless networks. We show that when communication range of nodes are properly controlled using power control, better load balancing can be achieved using shortest paths only. Such a strategy also decreases overall relaying in the network when compared to divergent routing schemes. We use the concept of *centrality* to achieve appropriate balance between relay burden of nodes and their power levels. Numerical results confirm that centrality based load balancing significantly improves network lifetime of sensor networks.**

I. INTRODUCTION

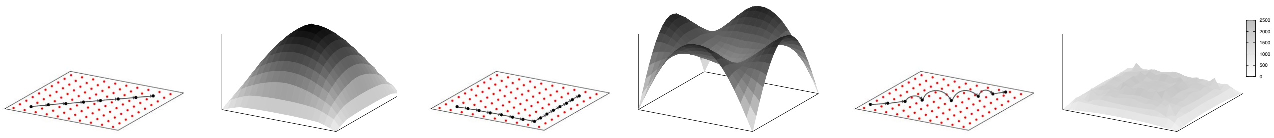
Many of the routing protocols proposed for multi-hop wireless networks are based on shortest path routing (SPR) due to its characteristics like simplicity and robustness. When SPR is employed in a large scale multi-hop network, certain nodes based on their position and traffic pattern have to perform disproportional amount of relaying for others [1]. Such *hot-spots* are often created near the center in uniform topologies [2] and also at cluster peripheries in case of clustered topologies. This increased congestion in certain areas has shown to be resulting into reduced network capacity. When the nodes are energy constrained, nodes performing higher amount of relaying than others deplete their batteries faster, reducing the overall network lifetime. As an example, when traffic flows between random source and destination pairs, network lifetime is often bounded by the lifetime of the nodes near the center since majority of the end-to-end shortest paths pass though them. On the other hand, when nodes send their data to a central entity (a sink or a gateway), generally one hop neighbors of the sink have to perform the most relaying which results into earlier depletion of their batteries [3], followed by disconnection of the sink from other alive nodes. In most cases, relay load distribution of nodes is significantly unfair where some nodes exhaust their batteries very quickly while others have not consumed even half of their energy resource.

The problem of disproportionate relaying and resultant shorter network lifetime is often addressed using *divergent* routing schemes where routing paths intentionally try to avoid passing via the nodes near the center. Examples of such schemes include devising curved paths in curve-ball routing [2], [4], one turn rectilinear paths in Manhattan routing [5] and edge reflection paths of outer space routing [6]. Any such divergent routing scheme increases relaying load of the nodes near the periphery of the network while taking away some relaying burden from the nodes around the center. This results into better overall load balancing. This advantage comes at a cost of various other sacrifices. Most of the divergent routing schemes depend on geometrical properties of the network (for mapping over symmetric space like torus or sphere) which limits their applicability to uniform topologies only. Routing paths in any such scheme are also longer (higher stretch factor) when compared to shortest routing paths. Moreover, divergent routing schemes sacrifice the fundamental advantages of SPR such as robustness, scalability and simplicity. In many cases, divergent routing schemes do not eliminate the hot-spots in the network because the relay load of the nodes near the center decreases moderately while the load on nodes around the periphery increases significantly. This results into only a moderate increase of lifetime of network since the relay load is not completely balanced among nodes.

One presumption in divergent routing schemes or any other load balancing strategy is that all nodes operate at Compow [7] power level and routing is performed on the resultant topology. In Compow, all nodes use a uniform power level which is minimum required to maintain network connectivity. Compow achieves better concurrency in link scheduling due to lesser interference but requires more relaying at nodes because of longer routing paths. In this paper, we propose power control as a way to balance relay load and improve the network lifetime of energy constrained networks. In our concurrent work in the context of wireless mesh networks, we have shown that if the communication range of nodes are properly increased by increasing their power levels, better relay load balancing can be achieved even when routing on the shortest paths. The fundamental advantage of such power control based load balancing is that it preserves all the benefits of shortest path routing and still achieves longer lifetime compared to divergent routing schemes. Because all the characteristics of shortest path routing is retained, such load balancing can be applied to any kind of arbitrary topologies (e.g. clustered) and traffic patterns where divergent routing schemes can not be applied. The proposed load balancing scheme does not route the data on divergent routes to avoid passing through the nodes near the center. Instead, the data is routed on the shortest paths only and the nodes which are expected to relay more packets for others are skipped or *jumped over*. In the case of uniform topologies, this results into longer hops being taken near the center which reduces the relay load burden of congested nodes without increasing the relay load of the nodes on the periphery. Since the relay load is better balanced among the nodes with actual reduction in overall relaying, the overall network lifetime is improved.

Longer hops in routing paths can only be achieved by controlling the communication range of nodes using power control. However, the cost of relay load balancing is the higher power that must be expended in these transmissions, and hence higher energy expenditure. Thus it is not at all clear a priori whether this approach will improve or actually deteriorate the energy constrained lifetime of wireless *sensor* networks. This

978-1-4244-6398-5/10/$26.00



(a) Shortest path routing (b) Hot-spot generation (c) A divergent routing (d) Load redistribution (e) Centrality power control (f) Load balancing

Fig. 1: General nature of path and relay load characteristics

question is the focus of the present paper. We show that, surprisingly, the higher power transmissions can have a net beneficial effect on network lifetime, and derive the conditions for this.

The proposed heuristic for load balancing assigns higher power levels to nodes which are expected to relay more packets. This has underlying requirement of estimating the relay load of nodes in advance so that communication range can be assigned to them accordingly. We calculate *betweenness* centrality of nodes which assigns every node a score based on their expected relay load. The centrality value is then used to assign every node a power level which is proportional to its expected relay load. This increases the connectivity of the nodes who were expected to relay more packets previously. When shortest paths between nodes are found in this new more connected network, they pass over congested nodes, producing better load balancing. We show that in such power control based load balancing almost all nodes relay nearly same amount of traffic for others which drastically increases the overall network lifetime.

The rest of the paper is organized as follows - we start by explaining network model and related assumptions in Section II. Section III presents our insights about the impact of power control on energy efficiency of WSNs; for ease of reference, we briefly describe our previous results regarding load balancing with power control and how betweenness centrality can be used in this context. Instead of devoting a separate section for related work, we discuss them in each individual section as and when necessary. We present several numerical results in Section IV and compare various approaches of load balancing with different network lifetime measures. We conclude in Section V with brief discussion of future work.

II. NETWORK MODEL AND PRELIMINARIES

We model the network graph using unit disk graph $G_U = (V, E, r)$ where V is the set of n nodes and for any two nodes u and v, there exists an edge $uv \in E$ if their Euclidean distance $d_{uv} \leq r$. When there is not explicit power control, all nodes are assumed to be operating at Compow power level. Compow range (r_{min}) is defined as minimum value of r such that G_U is connected. We refer to Compow graph of V as $G_C = (V, E_C, r_{min})$. When centrality based power control is performed all the nodes are assigned different power levels depending on their centrality score. Here, assignment of power levels can actually be interpreted as bounding the maximum power level of nodes. That is, if a node is assigned a higher power level, this does not mean that it will always transmit at new increased power level. If a neighbor is reachable at a lower power level, it will utilize that to communicate with it. We do not assume any specific signal propagation model because power level of node are presented in terms of their communication range. As an example, in Compow, all nodes operate at power level $P(r_{min})$ which is necessary and sufficient to achieve communication range of r_{min} at all nodes. Now, if a node wants to increase its communication range by a factor of f, it tunes its power level to $P(f \cdot r_{min})$.

In all cases, two widely used traffic patterns namely, uniform node-to-node and uniform node-to-sink are studied. In uniform node-to-node traffic, every pair of source and destination communicate with amount of traffic which is uniform across all such pairs. In uniform node-to-sink traffic, all nodes send uniform amount of traffic to the sink only. With consideration of dense node distribution, greedy geographical routing (where packet is forwarded to the neighbor which is nearest to the destination) also becomes shortest path routing and we use both names interchangeably. Without loss of generality, we assume that all nodes operate on the same channel.

III. LOAD BALANCING USING POWER CONTROL

Conceptual difference between load balancing using divergent routing and power control is depicted in Fig 1. Power control based load balancing strategy utilizes shortest routes only but nodes near the hot-spots are jumped over to reduce their relay load. Note that such congested nodes are almost always co-located and increasing their communication range allow them to skip over each other whenever possible. As described before, such power control based load balancing strategy has an underlying requirement of accurately predicting relay load of nodes for a given topology, which we discuss next.

A. Modeling Relay Load

Techniques of modeling the relay load have been limited to uniform topologies with assumptions like continuous density of nodes. Euclidean distance based modeling [2] and Voronoi cell based modeling [1] rely mainly on geometrical properties of the network and do not accurately accommodate underlying network connectivity. Due to these reasons, they are often not applicable to non-uniform topologies and different kinds of traffic pattern.

1) Betweenness Centrality: We are interested in devising a relay load estimation technique which relies on properties of network graph. Centrality indices [8] proposed for analysis of large network assign relative importance or status to every node in the network based on certain characteristic of interest. One such centrality named betweenness of a node depends on how many end-to-end shortest paths between other nodes of network actually pass through it. In node-to-node uniform traffic, a node is likely relay more data for others if it falls on relatively more number of shortest paths between other nodes. For a network graph G, if S_{xy} is number of shortest paths between vertices x and y and $S_{xy}(v)$ denotes number of shortest paths between x and y which pass through vertex v, then betweenness centrality of v (denoted by $(b(v))$) is

$$b(v) = \sum_{x \neq y \neq v \in V} \frac{S_{xy}(v)}{S_{xy}} \tag{1}$$

The fraction in (1) (also known as *pair-dependency*) can be interpreted as the probability that vertex v will be relaying data between vertices x and y. Betweenness centrality of a node can be regarded as measure of how important a node is in carrying out relaying of data for other nodes. As described in [8], straightforward usage of Dijkstra's algorithm for computing betweeneness of nodes can have running time of $O(n^3)$. Brandes's algorithm [8] can compute betweenness of all nodes in $O(nm)$ time for unweighted graphs and $O(nm + n^2 \log n)$ for weighted graphs, where m is number of edges in the graph.

B. Centrality-based Power Control

Following steps describe how betweenness indices are used to assign power levels to nodes.

1) For a given V, first Compow range (d_{min}) is determined and $G_C = (V, E_C, d_{min})$ is created.
2) Betweenness centrality of all nodes in G_C are calculated using Brandes's algorithm and are normalized using $\max\{b(v) \mid v \in V\}$.
3) Every node $v \in V$ is assigned a power level (P_v) as: $P_v = P_{min} + (b(v) \cdot (P_{max} - P_{min}))$, where $P_{min} \geq P(d_{min})$ to guarantee connectivity and $P_{max} \geq P_{min}$. Even if $P_{max} = P_{min} = P(d_{min})$, resultant graph is at least G_c.

Any such assignment is uniquely referred as $\psi(P_{min}, P_{max})$ and resultant more connected graph of betweenness centrality based power assignment is called G_B. We often set $P_{min} = P(d_{min})$ and vary $P_{max} = P(f \cdot d_{min})$ using a factor $f \geq 1$. In such case, P_{min} and P_{max} are dependent on d_{min} which is a property of V, only control parameter is f which we refer as *growth factor*. For any reasonable value of f, ψ results into increased power levels and communication range of nodes which were expected to relay more packets. Nodes near the center in uniform topologies have higher betweenness and are assigned higher power levels. As shown in Fig. 1f, this allows them to *jump over* other nearby congested neighbors. If a source and a destination are on opposite side of each other over the periphery, packet from source first starts progressing along shorter hops. As it reaches near the center, long-distance transmissions occur which results into longer hops, followed by fewer shorter hops at the end. This results into subsequent reduction of relay load of nodes near the center without increasing relay burden on nodes on periphery.

Foremost advantage of such load balancing using power assignment is that it can be applied to any kind of arbitrary topology like clustered where divergent routing mechanisms can not be applied. Also, centrality measure of nodes can be calculated for any specific set of shortest paths pertaining to traffic pattern of interest, which makes the mechanism applicable for load balancing in any other traffic patterns (e.g. node-to-sink uniform). We have analytically proven that increasing connectivity between nodes using above mentioned centrality based power assignment always results into better load balancing even when shortest paths are used for routing. We do not include the proof here due to space limitations. It is possible to prove that when more and more edges are added to given a graph on any V, worst case relay load consistently decreases. Putting it other way, for some V, if a graph becomes spanner of another due to reduction of communication range of one or more nodes, overall load balancing in the network becomes worse.

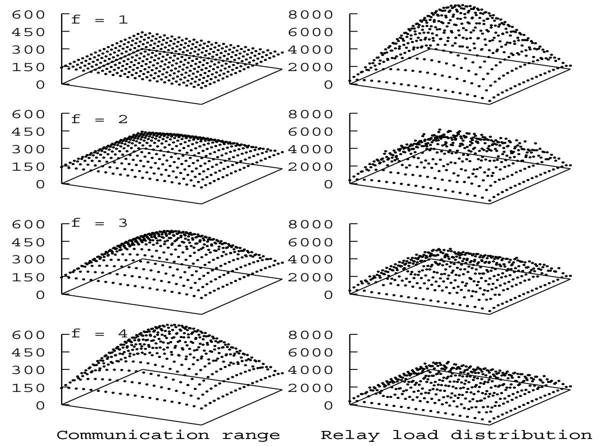


Fig. 2: Effect of growth factor on load balancing in 20x20 grid with uniform traffic

Fig. 2 shows the impact of growth factor on load balancing in a 20 x 20 grid network. As discussed before, P_{min} is set to $P(d_{min})$ and $P_{max} = P(f \cdot d_{min})$. Initially, when $f = 1$, $P_{max} = P_{min}$ and resultant topology is a Compow graph of V. In such case, there is no explicit effect of centrality values because growth factor is set to 1 and relay load distribution displays hot-spots near the center. When growth factor increases, the actual difference between maximum and minimum power level assigned in the network also increases. This results into higher power levels and communication ranges for nodes which have higher betweenness centrality and are expected to relay more packets. As can be observed in Fig. 2, central nodes are now assigned higher power levels which results into better load balancing. The growth factor f is a tunable parameter here and actual load balancing depends on its value.

C. Discussion

The centrality based load balancing mechanism increases connectivity between the nodes in the regions which were previously congested. As in Fig. 2 where f=4, nodes near the central hot-spot are assigned high communication range which results into reduced overall relaying in the area. It might appear at first that since some nodes in centrality based power control are transmitting at higher power levels and may deplete their batteries faster than other. But in fact number of transmissions required by such nodes are reduced significantly. Centrality based power control tries to achieve a balance between the nodes which have to transmit more number of times but with lower power levels and the nodes having to transmit at higher power levels but lesser number of times. The increase in energy expenditure for any given node is more than offset by the reduction in the transmission load of that node. This way, appropriate balance is achieved between actual amount of relaying and power level of nodes due to proper utilization of their betweenness values.

Apart from better load balancing, centrality based power control reduces the overall energy consumption because of reduction in total number of required transmissions and receptions. Reception is also a significant reason of power consumption in wireless sensor networks. It was shown in [9] that routing on shortest paths with least number of hops is almost always more energy efficient. When all nodes are operating at Compow power level, connectivity among the nodes are lesser than when they operate on centrality based power levels. So, shortest paths in topology resulting from centrality based power control will have lesser number of hops than shortest paths of Compow topology. This way, when routing uniform node-to-node traffic on shortest paths, centrality based power control requires lesser number of transmissions/receptions than Compow power control mechanism, which in turn results into lower overall power consumption.

Centrality based power control mechanism with shortest paths is also more energy efficient than divergent routing scheme with Compow power levels. Any divergent routing scheme of load balancing results into longer routing paths (more number of hops) when compared to shortest paths. This is typically measured using *average path stretch* of a routing scheme which can be defined as average ratio of hop-length of routing paths in a divergent routing scheme to hop-length of shortest routing paths. The path stretch and load balancing ratio display a trade-off ([10], [11]) in any divergent routing scheme which makes better load balancing with lower stretch factor inherently difficult. Hence, load balancing improves with increased path stretch which results into increased path lengths and more number of transmissions and receptions. As an example, it was shown in [6] that outer space routing consumes 1.4 times more energy than shortest path routing. Hence, in general case, divergent routing scheme would end up spending more energy than shortest path routing.

Collectively, centrality based power control mechanism reduces overall energy consumption when compared to divergent routing schemes. Also, the energy expenditure of nodes is also more uniform. This results into drastic overall increase of network lifetime of sensor networks.

IV. NUMERICAL RESULTS

We now present simulation results for load balancing followed by the numerical evaluation of sensor network lifetime.

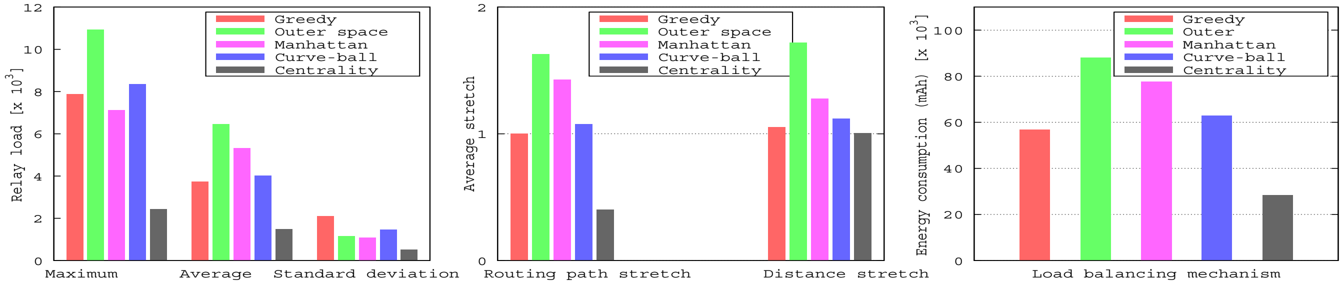
A. Load Balancing

Load balancing of greedy routing in centrality based power controlled topology is compared with the load balancing of greedy routing in Compow topology (G_C) and three well-known divergent routing schemes, namely outer space routing [6], Manhattan routing [5] and curve-ball routing [2]. In outer space routing, packets are first forwarded towards the periphery of the network and is then reflected back from some intermediate node towards the actual destination. In Manhattan one-turn routing, source forwards the packet to an intermediate node which is near the intersection of horizontal/vertical lines passing through the source and destination. In curve-ball routing, network plane is first mapped on a sphere and shortest paths on sphere are then mapped back to the plane. This results into center-avoiding curved routing paths. All divergent routing schemes are also employed in G_C.

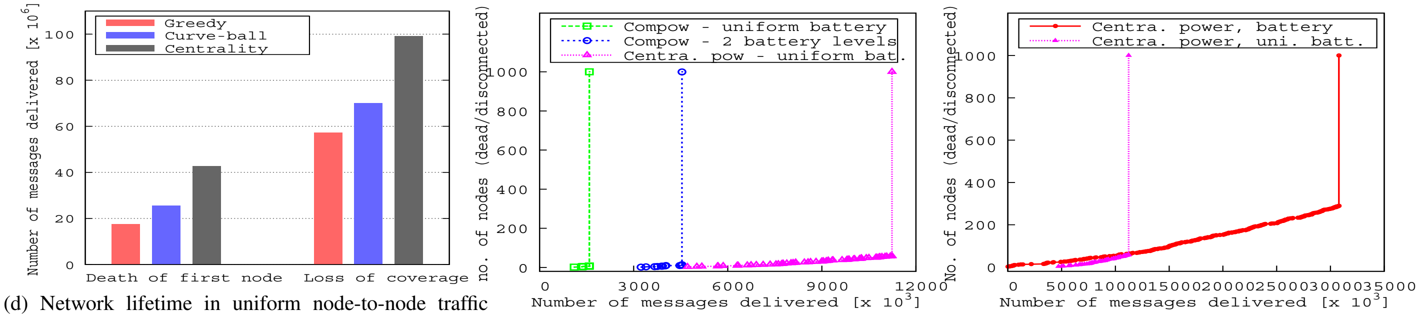
Fig.3a shows the results of load balancing in a 400 nodes network and uniform node-to-node traffic pattern. We use growth factor $f = 6$ in ψ as described in Section III-B. Centrality based power control mechanism achieves significantly better load balancing compared to greedy and divergent routing schemes. Divergent routing schemes increase the average relay load of nodes when compared greedy routing but decreases the overall deviation, which shows better load balancing. On the other hand, ψ decreases the standard deviation of relay load substantially without even increasing the average relay load. In most cases, ψ achieves upto 50% better load balancing than divergent routing schemes which is a useful practical result. Fig. 3b compares the average path stretch and distance stretch of these load balancing schemes. Average distance stretch can be defined as average ratio of Euclidean length of a routing path (summation of lengths of all hops) to actual Euclidean distance between source and destination. This measures on an average how much routing paths of a scheme deviates from the straight line between the endpoints. All the divergent routing schemes increase path and distance stretch compared to greedy routing in Compow graph. Different for this, ψ actually reduces path stretch below one. This is because power control increases the network connectivity and which reduces the number of hops required to be taken to reach the destination. Also, ψ reduces distance stretch when compared to Compow graph because increased connectivity makes end-to-end shortest paths to deviate less form the straight line.

B. Network Lifetime

In this section we present the numerical results for energy efficiency of load balancing mechanisms and resultant network longevity. We model our energy-constrained network as a sensor network where a typical example of the node can be a widely used MicaZ [12] node. Specifically, they utilize CC2420 [13] radio chip which offers as many as eight different transmission power levels. As described in [9], these Tx power levels have energy consumption in the form of $P_T(d) = P_{T0} + P_A(d)$ where $P_T(d)$ is the total power consumption to transmit at a distance d which contains a component P_{T0} independent of d and another component $P_A(d)$ dependent on d. The transmission range independent component $PT0$ also has a significant impact on overall consumption because no matter at what power level a transmission occurs, $PT0$ is always accounted for all transmissions in the network. The actual power consumption (in mA) at eight discrete power levels [13] are 8.5, 9.9, 11.2, 12.5, 13.9, 15.2, 16.5, 17.4 and typical reception power consumption is 12 mA. It is obvious that the presented scheme has a crucial dependence on actual signal propagation model and resultant communication range. As mentioned before, we do not assume a specific signal propagation model. Instead, for simulations, we rely on real-world measurements of MicaZ listed in [14] for the relationship between transmission power and corresponding communication range in standard outdoor environment. The maximum transmission range (d) achievable at various Tx power levels is determined in such a way that reception at



(a) Relay load compared to divergent routing (b) Path characteristics compared to divergent routing (c) Global energy consumption



(d) Network lifetime in uniform node-to-node traffic (n=1000)

(e) Network lifetime in node-to-sink traffic (f) Centrality based power and battery level allocation

Fig. 3: Effects of centrality based power control on load balancing, energy efficiency and network lifetime

distance d has above 95% packet reception rate [14]. It is assumed that power consumed in transmission and reception functions dominates the consumption of all other tasks and ideal MAC protocol is employed for low-level implementation. For simulations, continuous power levels resulting from centrality based power assignment are mapped to nearest higher discrete power level. Each node is powered by two AA batteries (2000 mAh, 3 V) and transmission of packets are assumed to be 500 ms long.

Fig.3c shows global energy expenditure with various load balancing schemes when every node in the network sends one packet to every other node in the network. As explained before, any divergent routing scheme consumes more energy that greedy routing because of increased path lengths. On the other hand, ψ reduces the total number of transmissions and receptions (path length) which results into reduced energy consumption. This is in line with results presented in [9] which shows that routing on shortest paths in a more connected network (lesser number of hops) is more energy efficient.

1) Uniform Node-to-node Traffic: We consider two measures of network lifetime in the case of uniform node-to-node traffic pattern: time to death of the first node and loss of coverage. These measures are discussed in [15] and are widely used in sensor network research. In both the measures, after certain number of messages are transferred between nodes, a node in the network ends up depleting its battery which is marked as the death of the first node. This first node is highly likely to be located near the center in the case of greedy routing and often has to perform maximum amount of relaying. Fig.3d shows comparison of death of first node based network lifetime in greedy routing, curve-ball routing and centrality based load balancing. Divergent routing schemes like curve-ball improves on time to the first death by better distributing the relay load in the network. The ψ improves the lifetime significantly because it achieves better load balancing than other mechanisms as shown in Section IV-A.

In the second measure of lifetime, it is assumed that every sensor has a role of sensing certain number of *event points*. Every every point is assumed to be covered by approximately 15 sensors. This way, when co-located 15 sensors die, a particular event point becomes uncovered, resulting into dysfunctional state of the network. This is different from the first measure because network can still continue performing its work even after the death of first node. As can be observed in Fig.3d that ψ achieves significantly longer lifetime because of better load balancing and reduced path lengths. As before loss of coverage occurs near the center for greedy routing and near the area between periphery and center in curve-ball routing. It was observed that in the case of ψ, loss of coverage happens almost uniform randomly in the network, which demonstrates improved load balancing.

Note that in the presented scheme as the power levels of nodes increase, overall interference also increases which results into degraded network capacity. In our contiguous work, we have systematically studied the effects of centrality based power control in node-to-node and node-to-sink traffic pattern. We have shown that network throughput and capacity is dependent of traffic pattern, offered load and the network topology. In case of node-to-sink traffic increasing power levels have positive effects on capacity while mixed effects are observed in case of node-to-node traffic pattern. We do not present capacity results here since the focus is on the network lifetime. Also, sensor network typically have lower volume of data transfer and increased throughput is not an objective considered in this work. It is also possible to tune the centrality parameters to achieve correct balance between load balancing and achievable network capacity.

2) Uniform Node-to-sink Traffic: Now we consider the uniform node-to-sink traffic pattern which is a more practical case for real world sensor deployments. Since all nodes are sensing and transferring their packets to the sink, disconnection of the sink from the nodes is a useful and accurate network lifetime measure [3]. Specifically, it was shown that when all the nodes providing connectivity to the sink (first tier nodes) exhaust their battery levels, sink can no longer be reached and the network becomes dysfunctional. Here it is also assumed that sink itself is not power constrained. When the sink is placed at the center of the network, there is no significant benefit of divergent routing because all the packets have to eventually traverse through the first tier nodes only. Hence, only SPR is considered here for comparison. In a typical lifetime of such a network, all nodes start by sending packets to the sink and nodes in first few tiers start depleting their batteries very quickly. At a certain point, a node, most probably in the first tier, dies but other nodes of the first tier still provides sink connectivity. As an when more and more first tier nodes die, it increases the relay load of remaining first tier nodes since all shortest paths to sink now pass through them. Eventually, all nodes in the first tier deplete their batteries and suddenly entire network becomes disconnected.

Such a case is displayed in Fig.3e where all nodes (n=1000) are assumed to be operating at Compow power level and have uniform battery levels too. Fig.3e depicts number of nodes that can not reach the gateway because either they have depleted their batteries or they are disconnected from the sink due to deaths of other nodes. Initially, most of such depicted nodes are the ones who have depleted their batteries and are mostly in first tier. Once all the nodes of first tier die, all remaining nodes suddenly become disconnected (vertical straight transition of the curve) and network lifetime has ended. It is worth noting that at this point nodes who are disconnected but yet not dead, have not even depleted half of their batteries in most cases.

To mitigate the problem, [3] presented an approach where nodes near the sink (first few tiers) are assigned higher battery levels than other in such a way that global battery budget remains unchanged. In the simplest case of their solution, there are two battery levels in the network where 13% of total nodes (near the sink) have 5718 mAh batteries while rest of 87% have batteries with capacity of 1442 mAh. Now, nodes who are responsible for relaying more packets are assigned higher battery levels to live longer and increase network lifetime. We simulate this case and results are presented in Fig.3e which shows that even with just two battery levels, overall network lifetime can be about three times longer than the base case. The third case presented in the Fig. 3e is the case of load balancing with centrality based power control. Here, the battery levels of the nodes remain uniform but as before, nodes which are likely to relay more packets for others are assigned higher power levels. This way, as we move from the periphery towards the sink in the center, power levels of the nodes increase in every tier continuously. This allows the nodes away form the sink to jump over the first few tiers' nodes and directly reach the sink which reduces their relaying burden. Hence, relay load of nodes are better distributed among the nodes even in case of node-to-sink traffic pattern (not possible with divergent routing schemes). This results into deaths of nodes which are relatively more consistent over time (Fig. 3e) and significant increase of network lifetime is observed.

Betweenness centrality can also be used to assign battery levels to the nodes since the nodes which are likely to perform more relaying are actually the nodes which deplete their batteries before others. Fig. 3f shows the lifetime behavior of a network where nodes which are likely to relay more packets (in first few tiers) for others are assigned higher power levels as well as higher battery levels. The same algorithm presented in Section III-B is also used to perform battery assignment in a way that overall battery budget remains unchanged. Different from discrete multiple battery level case, here the battery levels of the nodes change continuously. As can be observed in Fig. 3f, such a power and battery assignment results into substantially longer network lifetime. The lifetime is even better than the case where only power levels are assigned using centrality but the battery levels are uniform. Though the death of the first node occurs earlier than other cases, an interesting observation is that node deaths and disconnections are more consistent over the time and uniform across the network which shows improved balance between relay load distribution and battery resource allocation.

V. CONCLUSIONS AND FUTURE WORK

When centrality based power control is employed in the network, better load balancing can be achieved with shortest path routing. Various evaluations of network lifetime confirm that centrality based load balancing can increase network lifetime significantly in different traffic patterns. The presented scheme requires global knowledge for determining the centrality values and power levels. In future, we plan to extend the scheme for distributed calculation of centrality and devise a power control protocol for implementation.

REFERENCES

[1] S. Kwon and N. Shroff, "Paradox of shortest path routing for large multi-hop wireless networks," in *INFOCOM 2007*, May 2007, pp. 1001–1009.

[2] L. Popa, A. Rostamizadeh, R. Karp, C. Papadimitriou, and I. Stoica, "Balancing traffic load in wireless networks with curveball routing," in *MobiHoc '07*. New York, NY, USA: ACM, 2007, pp. 170–179.

[3] M. Sichitiu and R. Dutta, "Benefits of multiple battery levels for the lifetime of large wireless sensor networks," in *NETWORKING 2005*.

[4] F. Li and Y. Wang, "Circular sailing routing for wireless networks," in *INFOCOM 2008*, April 2008, pp. 1346–1354.

[5] D. K. S. Durocher, E. Kranakis and L. Narayanan, "Balancing traffic load using one-turn rectilinear routing," in *TAMC*, April 2008.

[6] A. Mei and J. Stefa, "Routing in outer space: fair traffic load in multi-hop wireless networks," in *MobiHoc '08*, 2008, pp. 23–32.

[7] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar, "The COMPOW protocol for power control in ad hoc networks," *European Wireless Conference*, 2002.

[8] U. Brandes and T. Erlebach, *Network Analysis: Methodological Foundations*. Springer-Verlag Berlin Heidelberg, 2005.

[9] Q. Wang, M. Hempstead, and W. Yang, "A realistic power consumption model for wireless sensor network devices," in *SECON '06*.

[10] J. Gao and L. Zhang, "Trade-offs between stretch factor and load-balancing ratio in routing on growth-restricted graphs," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 20, no. 2, pp. 171–179.

[11] F. Li and Y. Wang, "Stretch factor of curveball routing in wireless network: Cost of load balancing," in *ICC 2008*, pp. 2650–2654.

[12] Micaz mote module. [Online]. Available: www.xbow.com

[13] Chipcon cc2420. [Online]. Available: www.ti.com

[14] M. Mallinson, P. Drane, and S. Hussain, "Discrete radio power level consumption model in wireless sensor networks," in *MASS 2007*.

[15] D. M. Blough and P. Santi, "Investigating upper bounds on network lifetime extension for cell-based energy conservation techniques in stationary ad hoc networks," in *MobiCom '02*.