GeoQuorum: Load Balancing and Energy Efficient Data Access in Wireless Sensor Networks*

Jun Luo Ying He
School of Computer Engineering
Nanyang Technological University (NTU), Singapore
Email: {junluo,yhe}@ntu.edu.sg

***Abstract*—When data productions and consumptions are heavily unbalanced and when the origins of data queries are spatially and temporally distributed, the so called *in-network data storage paradigm* supersedes the conventional *data collection paradigm* in *wireless sensor networks* (WSNs). In this paper, we first introduce *geometric quorum systems* (along with their metrics) to incarnate the idea of in-network data storage. These quorum systems are "geometric" because curves (rather than discrete node sets) are used to form quorums. We then propose GeoQuorum as a new quorum system, for which the quorum forming curves are parameterized. Our proposal significantly expands the quorum design methodology, by endowing a system with a great flexibility to fine-tune itself towards different application requirements. In particular, the tunability allows GeoQuorum to substantially improve the load balancing performance and to remain competitive in energy efficiency. Our simulation results confirm the performance enhancement brought by GeoQuorum.**

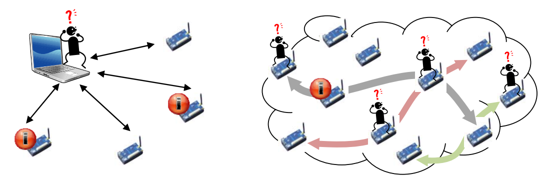
I. Introduction

Since their inception, *wireless sensor networks* (WSNs) bear the task of intensive data collection through their large scales and dense deployments, which represents a significant improvement over traditional sensing systems [1]. However, the limited energy storage of a node heavily confines WSNs' ability of accomplishing their missions. The related research proposals to cope with this issue mainly focus on two objectives: namely *load balancing* and *energy efficiency* [2].

A WSN is often supposed to gather data from a large set of nodes to a particular (often small) set of nodes. The resulting *convergecast* type of data transmission pattern makes the above two objectives contradict each other. For example, energy efficient communication protocols may lead to very unbalanced load distribution [3]. Fortunately, we will demonstrate a better tradeoff between these two objectives under another data access paradigm involving *in-network data storage*. This latter paradigm also endows a great flexibility to data access: it can be performed whenever and wherever needed. Here we first provide an illustration to contrast the two data access paradigms in Fig. 1. It is clear that, whereas the convergecast collects the data at a single point, the in-network storage replicates data at various nodes, to which a later data query is directed.

In this paper, we focus on a particular design methodology, *quorum systems*, under the in-network data storage paradigm.

*This work is supported in part by AcRF Tier 1 Grant RG 32/09 and 69/07.



(a) Convergecast (b) In-network data storage

Fig. 1. Comparison of two data access paradigms.

Specifically, data produced by sensor nodes and queries generated by human users are both directed to certain *quorums* (subsets of nodes). As the intersection between quorums are guaranteed in the design phase, users may access the sensory data without directly communicating with the sources that generate those data. Although quorum systems exist in distributed systems [4], we are reviving them in the sensor networking scenarios. Moreover, our design method, namely, *geometric quorum systems* (GQS), leverages on the recent developments in conformal geometry [5], and we propose GeoQuorum where the quorums are formed by parameterized curves. Tuning the parameters that determine the quorums allows us to flexibly identify desired tradeoffs between load balancing and energy efficiency. Through both analysis and simulations, we further demonstrate that our design outperforms the existing ones in terms of both load balancing and energy efficiency. In summary, our main contributions are:

- A formal definition of GQS and the related metrics.
- A thorough analysis of the existing quorum system designs for WSNs against the defined metrics.
- A general conformal geometry based quorum design methodology that applies to WSNs with any shape of the network areas.
- A specific quorum system, GeoQuorum, formed by parameterized curves, allowing a flexible tradeoff to be made between load balancing and energy efficiency.

The remaining of this paper goes as follows. In Sec. II, we define quorum systems (in the traditional sense) and their metrics, and we also briefly review the application of quorum systems in networked settings, in particular a recent geometry-based quorum system design. We focus on GQS in Sec. III. Starting with the conformal geometry basics and network model in Sec. III-A, we formally define GQS in Sec. III-B, we then propose GeoQuorum in Sec. III-C. We report the simulation results in Sec. IV and conclude our paper in Sec. V.

II. Fundamental of Quorum Systems

A. Basic Definitions

Quorum systems represent a fundamental abstraction for coordination among the nodes of a distributed system (e.g., a set of networked nodes). In its traditional sense, a quorum system is defined upon a finite set (also termed *universe*) $\mathcal{U} = \{u_1, u_2, \cdots, u_n\}$ of nodes. In particular, the following definition characterizes a quorum system [4].

Definition 1 (Quorum System): A quorum system $\mathcal{Q} \subset 2^{\mathcal{U}}$ is a set of subsets of $\mathcal{U}$ such that every two subsets intersect. Each $Q \in \mathcal{Q}$ is called a *quorum*.

Given a quorum system $\mathcal{Q}$, a node may choose to *access* a quorum by either *writing* to or *reading* from it. Thanks to the intersection property, a read access will find the desired data from some quorum that stores the data written by another node. Taking into account the inherent asymmetry between read and write accesses, we may redefine the quorum system in a asymmetric fashion as follows [6], the earlier definition hence specifies *symmetric* quorum systems.

Definition 2 (Asymmetric Quorum System): An asymmetric quorum system $\mathcal{Q} \subset 2^{\mathcal{U}}$ consists of two disjoint sets, $\mathcal{Q}^R$ and $\mathcal{Q}^W$, of subsets of $\mathcal{U}$, such that each subset in $\mathcal{Q}^R$ intersects every subset in $\mathcal{Q}^W$. Each subset in $\mathcal{Q}^R$ (resp. $\mathcal{Q}^W$) is called a *read* (resp. *write*) *quorum*.

B. Metrics on Quorum Systems

We introduce two metrics to measure the performance of quorum systems, namely, *load* and *robustness*.

1) Load: This metric measures the computational load taken by individual nodes due to their participation in various quorums. Obviously, it depends not only on how a quorum system is constructed, but also on what strategy individual nodes adopt to access the system.

Definition 3 (Access Strategy): An access strategy S consists of an *access rate* λ_S and a probability measure P_S on $\mathcal{Q}$, i.e., $\sum_{Q\in\mathcal{Q}} P_S(Q) = 1$. The strategy is *pure* if $P_S(Q) = 1$ for some $Q \in \mathcal{Q}$; otherwise it is *mixed*.
For asymmetric quorum systems, we replace $\mathcal{Q}$ by $\mathcal{Q}^R$ or $\mathcal{Q}^W$, depending on which access operation is under consideration.

Definition 4 (Load): The load induced by S on a node u_i is

$$\ell_S(i) = \sum_{Q\in\mathcal{Q}:u_i\in Q} \lambda_S P_S(Q).$$

The *system load* induced by S on a quorum system $\mathcal{Q}$ is the maximal load induced by S on any node in $\mathcal{U}$, i.e.,

$$\mathbb{L}_S(\mathcal{Q}) = \max_{u_i\in\mathcal{U}} \ell_S(i).$$

Intuitively, this metric measures the evenness of load distribution within the whole system: the lower the system load, the more balanced the load is distributed.

2) Robustness: As another important metric, *robustness* indicates the ability of a quorum system to cope with node failures (viz. its fault tolerance). Many measures have been proposed for this metric, we choose the most straightforward one: the size of the intersection between two quorums.

Definition 5 (Robustness): The robustness of a quorum system $\mathcal{Q}$ is the size of the minimum intersection between an arbitrary pair of quorums

$$\mathbb{R}(\mathcal{Q}) = \min_{Q_i,Q_j\in\mathcal{Q}} |Q_i \cap Q_j|.$$

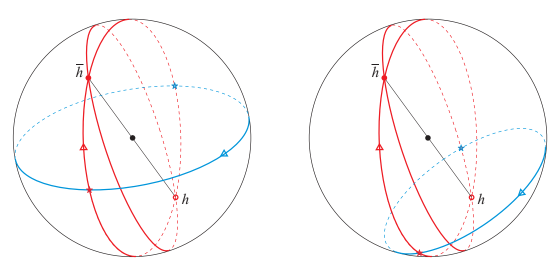
For asymmetric quorum systems, $Q_i, Q_j \in \mathcal{Q}$ is hence replaced by $Q_i \in \mathcal{Q}^W$ and $Q_j \in \mathcal{Q}^R$.
It is straightforward to see that, if the system robustness is k, then any node failures involving less than k nodes will not affect the intersection property of the system.

C. Related Work on Conventional Quorum Systems

Traditional quorum systems are confined in 2D space, e.g., a grid-like design [7], [8]. These designs are often so rigid that they allow very little tunability that adapts a system to various application requirements. To improve the flexibility of the quorum systems, *probabilistic quorum systems* [9] were introduced to relax the intersection rule (making it a random variable) and to leave more freedom in trading load for robustness. Interested readers are referred to [10], [6] for later developments on probabilistic quorum systems in coping with mobility. In general, as nodes in WSNs are often static, we advocate a deterministic design for quorum systems, while relying on other techniques (rather than pure randomization) to improve its flexibility.

D. Quorum Systems in A Projective Space

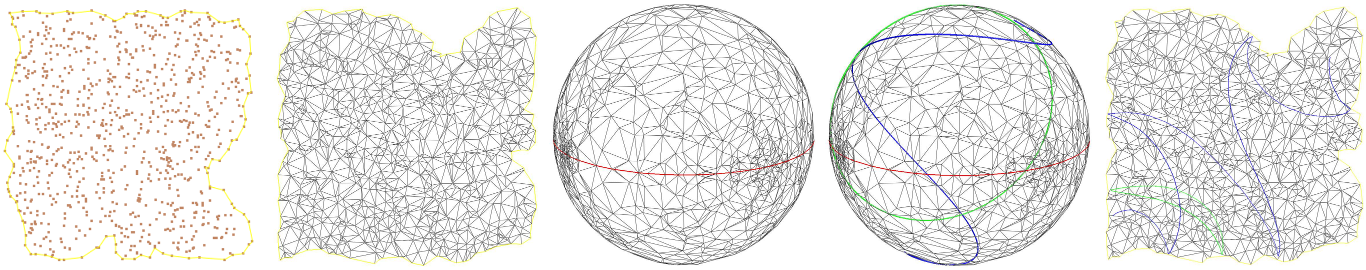
Recently, a new design methodology for (deterministic) quorum systems was proposed in [11]. This method suggests using projective map to first "lift" the 2D network area onto a 3D surface, a sphere, then design quorum systems on the 3D surface, and finally project the designed system back to the 2D area. As the system design done in a 3D space allows more diversity in "shaping" the quorums, more flexible system designs become possible. The practicality of this design approach is backed by efficient localization mechanisms (e.g. [12]), as well as the *trajectory based forwarding* [13], which may perform data forwarding along a continuous curve. Given a certain data type, two designs are proposed in [11]:[1]



(a) Symmetric quorum system $\mathcal{Q}_G$ (b) Asymmetric quorum system $\mathcal{Q}_L$

Fig. 2. Quorum systems designed in [11]. We use red (resp. blue) color to indicate quorums accessed by a write (resp. read) access. For quorums in red, the corresponding geographical hash location h and its antipodal point $\bar{h}$ are shown. We also use pentagrams to represent the intersection between quorums, and triangles to represent the nodes that access a quorum.

[1] In the original paper, a quorum system design is termed a *double ruling scheme*. The two designs we discuss here are named *double rulings retrieval* and *distance-sensitive retrieval*.



(a) (b) (c) (d) (e)

Fig. 3. Taking an arbitrary simply connected region D and a node set inside it as input (a), our design starts with a Delaunay triangulation [14] and a construction of a closed genus-0 surface $\bar{D}$ by double covering, i.e., replicate D to D', reverse D''s orientation, and glue D and D' along the common boundary (b). Then $\bar{D}$ is conformally mapped to the unit sphere, such that the original boundary ∂D is the equator, the red circle in (c). Note that the input region D and its copy D' are mirror reflected with respect to the equator. This design allows us to use various spherical curves to form quorums, such as circles and spirals shown in (d) and their inverse-map in D (e).

$\mathcal{Q}_G$ Symmetric quorum systems with each quorum represented by a great circle, shown in Fig. 2(a). The access strategy for a write access is pure as the corresponding great circle is fixed by two points: the node accesses a quorum and the geographical hash h of the data type.

$\mathcal{Q}_L$ Asymmetric quorum systems with write quorums represented by great circles and read quorums by latitude circles, shown in Fig. 2(b). While the access strategy for a write access is the same as the first design, that of a read access also becomes pure, as the circle of each read quorum is also defined by the node access the quorum and the geographical hash h of the data type.

In terms of quorum system design, apart from presenting heuristics, no rigorous definitions and metrics are provided for the quorum systems in [11], thus no formal analysis is given to evaluate the performance of the designed system. Also, only planar curves are used to represent quorums on the 3D surface, which significantly confines the design flexibility.

III. Geometric Quorum Systems for Data Access

In this section, we first introduce the geometry background and define our network model, along with the properties and metrics of geometric quorum systems (GQS). Then we present our asymmetric quorum systems, GeoQuorum, that makes use of spatial curves to substantially improve the flexibility in fine-tuning system performance.

A. Background on Computational Conformal Geometry

Computational conformal geometry (CCG) is an emerging research field spanning computer science and pure mathematics [5]. Intuitively speaking, a conformal map is a function that preserves the angles. Here we briefly discuss the CCG tools that we will use in this paper, which is also illustrated in Fig. 3. Given a simply connected shape $D \in \mathbb{R}^2$ with boundary ∂D and a node set inside it, we construct $\bar{D}$ as a closed surface of genus 0 (as explained in Fig. 3). We then compute a harmonic function ϕ mapping $\bar{D}$ to the unit sphere, i.e., $\phi : \bar{D} \to \mathbb{S}^2$ such that $\triangle\phi = 0$ where $\triangle$ is the Laplace-Beltrami operator. This map has the following promising properties:

- ϕ is conformal, thus, there is no angle distortion;
- $\phi(D)$ and $\phi(D')$ are mirror reflected with respect to the equator;
- The map applies to any 2D simply connected region D.

Here we should emphasize that the harmonic map based method as mentioned above allows us to map arbitrary simply connected region to cover the whole sphere, thus avoiding various issues involved in stereographic projection [11], such as mapping north pole to infinity and hence making potential quorum intersections out of the network boundary.

B. Network Model and Geometric Design Basics

We represent a WSN by $\mathcal{U}$, with $u_i \in \mathcal{U}$ being a sensor node. $\mathcal{U}$ also serves as the universe upon which a quorum system can be defined.

1) Geometric Model of WSNs: We apply the tool discussed in Sec. III-A to map the network area to a sphere of **unit radius**. For the reverse projection, any curve that passes across the equator has its upper and lower sections projected separately to the two network areas. Then two (projected) sections are combined to get the projection on the original network area, as shown in Fig. 3(e). This improved map allows us to perform geometric analysis on the whole sphere surface.

2) Geometric Quorum Systems: We extend the conventional definitions for quorum systems (presented in Sec. II-A) to geometric quorums system (GQS).

Definition 6 (Geometric Quorum System): A GQS $\mathcal{Q}$ is a set of curves in space $\mathcal{A}$ ($\mathcal{U} \subset \mathcal{A}$), such that every two curves intersect. Each curve in $\mathcal{Q}$ defines a quorum.
The definition for asymmetric quorum systems is omitted; one simply splits $\mathcal{Q}$ into $\mathcal{Q}^W$ and $\mathcal{Q}^R$, and intersection is only required between the two sets. We keep using the same definition for access strategy (*Definition 3*), load (*Definition 4*), and robustness (*Definition 5*). The load taken by a node is the energy consumption for it to **transmit** the data (for write) or queries (for read) to quorums in which it involves.

Unlike traditional distributed systems, the energy efficiency (or total energy consumption of the whole WSN) is also a major concern of WSNs. Let $M(Q) = |\{u \in \mathcal{A} | u \in Q\}|$ be a measure of the total energy consumption of a quorum Q, we further define a metric to measure this performance aspect.

Definition 7 (Total Load): The total load induced by S on a certain quorum $\mathcal{Q}$ is

$$\mathbb{L}_T(\mathcal{Q}) = \sum_{Q \in \mathcal{Q}} \lambda_S P_S(Q) M(Q).$$

In general, each node may take a different access strategy. To simplify the analysis, we only distinguish between two types of strategies, namely S_R and S_W for read and write respectively.

C. GeoQuorum: System with Spatial Quorums

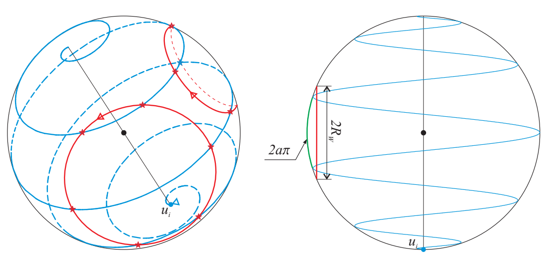
Our analysis in [15] shows that $\mathcal{Q}_G$ and $\mathcal{Q}_L$ have (i) limited robustness ($\mathbb{R}(\mathcal{Q}) = 1$), (ii) unbalanced load distribution (large $\mathbb{L}_S(\mathcal{Q})$ due to the pure access strategy), and (iii) no flexibility to be fine-tuned, hence they cannot adapt to different access rates. In this section, we present GeoQuorum as a new design. GeoQuorum makes use of spatial curves to form quorums, hence allows a great deal of freedom in fine-tuning the system performance. GeoQuorum is an asymmetric quorum system, with write and read quorums formed by different type of curves. Specifically, we have

- **write quorums** are formed by circles with adjustable radius R_W that can be tuned according to the access rate.
- **read quorums** are formed by a special spherical spiral, defined as follows:

$$x = \cos(\theta + \theta_0) \cos\phi, \quad y = \sin(\theta + \theta_0) \cos\phi, \quad z = \sin\phi$$

  where $\phi = a\theta$ and $\phi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$. Let α be the angle (with respect to the sphere center) between two consecutive loops ($\Delta\theta = 2\pi$), we have $\alpha = 2a\pi$. The parameter a is determined by R_W and the required robustness.
- **access strategy** is mixed: a **write quorum** is randomly chosen among all circles passing through the node that executes a write access; a **read quorum** starts from the node that executes a read access and ends at its antipodal point, with a randomly chosen θ_0.

We illustrate such a quorum system in Fig. 4(a). Note that



(a) GeoQuorum (b) Proof of *Proposition 1*

Fig. 4. Geometric quorum system designed using spatial curves in 3D.

the current design is based on the assumption that $\lambda_W > \lambda_R$; otherwise we adopt a dual design where we swap the write and read quorums. We first show the relation between R_W and a by the following proposition.

Proposition 1: If $R_W \geq ka\pi, a \in (0, 0.5)$, then the robustness of GeoQuorum is at least $2k$.

An intuitive explanation is sketched in Fig. 4(b). Given a certain robustness requirement, we have a one-to-one correspondence between R_W and a: $R_W = ka\pi$, as choosing the smallest circle minimizes the incurred system and total load. Under the assumption that $\lambda_W > \lambda_R$, we may choose to tune R_W according to λ_W/λ_R (the higher the ratio the smaller R_W is), then we match a to R_W based on the required robustness. Due to the use of mixed access strategy and the parameterized design, GeoQuorum can be tailored to meet the application requirements, such that both system load and total load can be reduced; which we will show in Sec. IV-B. Interestingly, our design includes $\mathcal{Q}_G$ and $\mathcal{Q}_L$ as special cases. We refer reader to [15] for detailed discussions.

IV. Simulations

We hereby use simulation results to confirm the advantages of GeoQuorum over the existing designs.

A. Simulation Settings

We randomly put nodes in a square area (scenarios with irregular areas are omitted due to space limitation). Then we use Delaunay triangulation to generate the connectivity graph. If a quorum (curve) passes through a triangle, all the three vertices are charged with a unit of communication load. This stems from the broadcast nature of wireless communication and the need for local coordination in the trajectory based forwarding. We assume WSNs with 5000 nodes. There is one data type, 500 nodes are contributing to it and 100 nodes may query it. We normalize the data query rate to 1 and vary the data production rate r to test the system performance. Note that the actual write and read access rates (to a quorum system) are $500r$ and 100, respectively. Such an asymmetry between data production and consumption is reasonable, as otherwise multiple convergecasts may lead to better performance. For each value of r, we obtain simulation results for 10 WSNs and show the mean value and, if necessary, the standard deviation.

B. Comparing GeoQuorum with Existing Designs

We compare GeoQuorum with $\mathcal{Q}_G$ and $\mathcal{Q}_L$. To make them comparable, we apply the respective quorum designs to our CCG design space. For GeoQuorum, we set $R_W = 0.2\pi$ and $a = 0.2$. We first compare the system load of the three quorum systems in Fig. 5(a), then their total load in Fig. 5(b). We also illustrate the actual load distribution in Fig. 5(c)-(d); the load distribution of $\mathcal{Q}_L$ is omitted, as it differs from $\mathcal{Q}_G$ only by about 1% to 2%. The following observations are immediate from these figures:

- Compared with GeoQuorum, the load distributions of $\mathcal{Q}_G$ and $\mathcal{Q}_L$ are very unbalanced, exactly due to the existence of a hash location h and its antipodal point $\bar{h}$.
- GeoQuorum incurs a much lower total load compared with all other three systems, due to its adaptivity to the asymmetry in data production and consumption.

C. Tuning the Load and Robustness of GeoQuorum

We show the performance of our GeoQuorum under parameter fine-tuning in this section. We first tune the spiral parameter a from 0.025 to 0.3 while increasing R_W proportionally to maintain the same robustness. The results on system and total

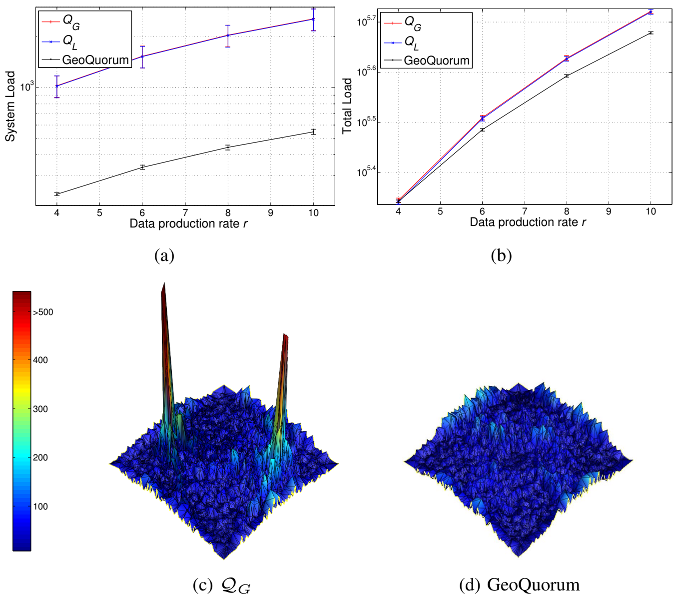


Fig. 5. Comparing GeoQuorum with $\mathcal{Q}_G$ and $\mathcal{Q}_L$.

load are plotted in Fig. 6(a) and 6(b), respectively. We only show mean values, as the standard deviations are too small to be discerned (partially due to the load balancing effect brought by GeoQuorum).

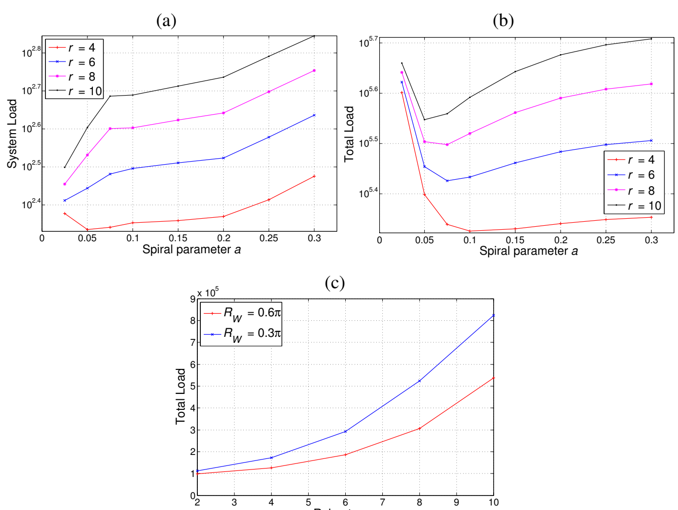


Fig. 6. Tuning the system performance.

In general, one always has to make a tradeoff between load balancing and energy efficiency. The tunability of GeoQuorum allows us to make different tradeoffs upon different application requirements. For example, when the data production rate is low ($r = 4$), $a \in (0.75, 1.5)$ appears to achieves a balanced performance in both system and total load. This region shifts towards smaller values with an increasing r. For $r = 10$, a is better to be around 0.05. The flexibility of freely tuning the system performance is one of the major advantages of GeoQuorum over the existing designs.

The robustness of GeoQuorum can be tuned by changing a but keeping R_W constant. As shown by *Proposition 1*, the robustness is tuned at a granularity of 2 under current setting; though fractional granularity can be achieved through randomization. Of course, increasing robustness comes at a cost of an increased total load, and we show the relation between robustness and total load by Fig. 6(c). We consider two cases where $R_W = 0.6\pi$ and $R_W = 0.3\pi$. When we tune a to linearly increase the robustness from 2 to 10, the total load increases by (roughly) following a power law.

V. Conclusion

We have investigated the issue of data access in WSNs, aiming at balancing (communication) load distribution while maintaining energy efficiency. Specifically, we have revived the application of quorum systems in WSNs, and proposed the concept of geometric quorum systems based on a new development in combining computational conformal geometry with sensor networking. In particular, we have proposed GeoQuorum that makes use of parameterized spatial curves to form quorums, such that the system performance can be fine-tuned to meet different application requirements. Through both analysis and simulations, we have confirmed the advantages of GeoQuorum over existing proposals.

References

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A Survey on Sensor Networks," *IEEE Communication Mag.*, vol. 40, no. 8, pp. 104–112, 2002.

[2] J. Ahn and B. Krishnamachari, "Fundamental Scaling Laws for Energy Efficient Storage and Querying in Wireless Sensor Networks," in *Proc. of the 7th ACM MobiHoc*, 2006.

[3] J. Luo and J.-P. Hubaux, "Joint Sink Mobility and Routing to Increase the Lifetime of Wireless Sensor Networks: The Case of Constrained Mobility," *IEEE/ACM Trans. on Networking*, vol. 18, no. 3, pp. 871–884, 2010.

[4] D. Malkhi and M. Reiter, "Byzantine Quorum System," *Springer Distributed Computing*, vol. 11, no. 4, pp. 569–578, 1998.

[5] X. Gu, F. Luo, and S.-T. Yau, "Recent Advances in Computational Conformal Geometry," *Comm. Inf. Sys.*, vol. 9, no. 2, pp. 163–196, 2009.

[6] J. Luo, P. Eugster, and J.-P. Hubaux, "Pilot: Probabilistic Lightweight Group Communication System for Ad Hoc Networks," *IEEE Trans. on Mobile Computing*, vol. 3, no. 2, pp. 164–179, 2004.

[7] M. Naor and A. Wool, "The Load, Capacity and Availability of Quorum Systems," *SIAM J. on Computing*, vol. 27, no. 2, pp. 423–447, 1998.

[8] Z. Haas and B. Liang, "Ad Hoc Mobility Management with Uniform Quorum Systems," *IEEE/ACM Trans. on Networking*, vol. 7, no. 2, pp. 228–240, 1999.

[9] D. Malkhi, M. Reiter, and A. Wool, "Probabilistic Quorum Systems," *Elsevier Info. and Comp.*, vol. 170, no. 2, pp. 184–206, 2001.

[10] J. Luo, J.-P. Hubaux, and P. Eugster, "PAN: Providing Reliable Storage in Mobile Ad Hoc Networks with Probabilistic Quorum Systems," in *Proc. of the 4th ACM MobiHoc*, 2003.

[11] R. Sarkar, X. Zhu, and J. Gao, "Double Rulings for Information Brokerage in Sensor Networks," in *Proc. of the 12th ACM MobiCom*, 2006.

[12] J. Luo, H. Shukla, and J.-P. Hubaux, "Non-Interactive Location Surveying for Sensor Networks with Mobility-Differentiated ToA," in *Proc. of the 25th IEEE INFOCOM*, 2006.

[13] D. Niculescu and B. Nath, "Trajectory Based Forwarding and its Applications," in *Proc. of the 9th ACM MobiCom*, 2003.

[14] J. Shewchuk, "Triangle: Engineering a 2D Quality Mesh Generator and Delaunay Triangulator," in *Springer LNCS 1148*, 1996, pp. 203–222.

[15] J. Luo and Y. He, "GeoQuorum: Load Balancing and Energy Efficient Data Access in Wireless Sensor Networks," 2010. [Online]. Available: http://arxiv.org/abs/1101.0892