Distributed Mobility Transparent Broadcast in Mobile Ad Hoc Networks

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***Abstract*— In this paper we propose a distributed, mobility transparent broadcast (DMTB) protocol to achieve ef£cient and effective broadcast in mobile ad-hoc networks. The protocol is fully distributed and highly adaptive to node mobility. It does not demand any neighborhood information and incurs little overhead. On one hand, the cross-layer design approach helps achieve effective broadcast with higher ef£ciency and alleviated interference; on the other hand, the proposed protocol achieves network energy balance by randomly rotating the set of relay nodes in different broadcast events even when the network topology stays unchanged. The protocol's performance is proved to be within a constant of the optimum. Detailed analysis regarding the broadcast interference, node density and protocol overhead is presented. DMTB is not only ef£cient, but also robust against node failures and scalable with the node density or the network area size.**

I. Introduction

The design of ef£cient broadcast schemes in wireless mobile ad-hoc networks is highly challenging due to various constraints and gets more complicated when node mobility is taken into consideration. The major concern of a broadcast protocol is which node should relay the broadcast message so as to achieve a high broadcast delivery rate at the cost of minimum resource consumption. In this paper the problem of interest is *how to ef£ciently broadcast in ad-hoc networks with high mobility*. To address this issue, we present a "distributed, mobility transparent broadcast (DMTB)" protocol that is not only ef£cient and effective, but also highly adaptive to node mobility. By "mobility transparent" we mean that node mobility does not degrade the protocol's performance.

For ef£cient broadcasting, ideally only nodes in the Minimum Connected Dominating Set (MCDS) should be elected as relay nodes, and identifying the MCDS is known to be NP-hard [2]. Since the problem of interest is broadcast in mobile ad hoc networks, many algorithms in literature such as [10], [11], [12] are not applicable since they are highly energy-consuming and incur severe overhead while constructing or maintaining the spanning tree. While protocols based on gossiping [4], [3] are ¤exible and distributed, their rebroadcast probability should be kept suf£ciently high (0.65-0.7) to prevent the broadcast from dying too fast [4]. Broadcast protocols which base their decisions on local information [5], [9] or are source-speci£ed [6] have also been proposed. However, the effectiveness and ef£ciency of these protocols depends on how fast the neighborhood information is updated and the likelihood of £nding a node at a desired location, both of which deteriorate as the mobility of nodes increases. In addition, although MAC layer interference is one of the biggest issues for broadcast in ad-hoc networks, all broadcast schemes mentioned previously are designed without taking it into consideration.

As described above, the design challenges involves both routing layer and MAC layer issues. To address these challenges, we resort to a cross-layer design and propose a constellation based, fully distributed broadcast protocol to achieve the broadcast effectiveness, ef£ciency, and mobility transparency. The protocol does not require any neighborhood information and has little overhead. MAC layer properties are taken into consideration during the designing to improve the energy ef£ciency and reduce collisions.

The rest of this paper is organized as follows. The next section introduces the proposed protocol. Section III presents an analysis of the protocol's performance. Finally, Section IV presents the simulation results and in the last section we present the concluding remarks.

II. The DMTB Protocol

A. The Background and Assumptions

To overcome the network mobility and performance degradation induced by unavailability of global information, DMTB employs an imaginary constellation as the reference to locate the relay nodes. DMTB assumes that nodes are only aware of their own geographical location and no neighborhood information is required. The constellation, shown by the dark solid lines in Fig. 1, spans the whole network and is anchored in each broadcast event by the source node. In the ideal case, nodes located exactly at the vertices act as the relay nodes and all others as non-relay nodes. The two theorems below provide the theoretical foundation for the constellation structure.

Theorem 2.1: If overlapping and gaps are not allowed and only one type of polygon is used, a plane can only be tiled by triangle, square or hexagon.
Proof of this theorem is presented in the Appendix I.

Theorem 2.2: Overlapping with hexagon tiling is the least among the three polygon tiling methods (hexagon tiling, triangle tiling or square tiling).
This can be proved by using a method similar to that used in [1]. From theorems above it can be seen that hexagon tiling has the highest broadcast ef£ciency.

The ideal scenario described above is impractical to realize since in many ad-hoc network application scenarios, it is dif£cult or even impossible to £nd a node that is located exactly at the required position. Construction and maintenance of the constellation may also introduce signi£cant overhead. This motivates our design of an "imaginary constellation" based and fully distributed broadcast protocol. In following sections we will elaborate upon the DMTB protocol. The vertices shown in Figure 1 will be referred to as the *benchmark positions*, and the distance between two neighbor vertices as the *cell radius*. The constellation in Figure 1 has another advantage that each area in the network is covered more than once. This provides certain resilience against message losses due to link failure or interference.

B. The DMTB Protocol Description

1) The Imaginary Constellation and the Benchmark Position Association Function: The imaginary constellation can be speci£ed by its origin, *cell radius* r and orientation θ. Each time a source node broadcasts a message, it formulates the broadcast message in the format shown in Figure 3(a). The message supplies important information to anchor the reference constellation: the constellation's origin (x_s, y_s), *cell radius* r and orientation θ_s (randomly generated within the range of $[0, \frac{2}{3}\pi]$). This information is enough to £x the reference constellation that spans the whole network, which means all benchmark positions are implicitly £xed. Note that the orientation θ_s is randomly selected for each broadcast event so that the nodes forming the constellation change for different broadcast events, even when the broadcast source or the network topology stays unchanged. This helps balance the energy consumption across the whole network so that the same set of nodes are not over-employed and die before others.

Upon reception of a broadcast message for the £rst time (duplicate messages are discarded), a node identi£es its benchmark position *p* and prepare the broadcast message according to *p*'s information. Figure 1 gives a constellation example with all vertices as the benchmark positions. The gray dashed line forms a Voronoi tessellation and each Voronoi cell contains one of the benchmark positions at the cell center. The property of Voronoi tessellation guarantees that an arbitrary node is closer to the benchmark position that is located in the same Voronoi cell. As shown in Figure 1, all nodes within the one Voronoi cell will mark themselves as the relay candidates for the benchmark position in the same Voronoi cell. In Figure 2, suppose a broadcast message is generated from the source node, with the constellation origin located at (x_s, y_s), and the broadcast message is shown in Figure 3(a). Node i £rst receives this broadcast message from its neighbor node j, with the message content shown in Figure 3(b). With node i's location given by (x_i, y_i), the received broadcast message will trigger node i to calculate its nearest benchmark position (x_i^p, y_i^p), which equals (x_A, y_A) in Figure 2. Please refer to Appendix II for details about how to calculate (x_i^p, y_i^p) based on the source node's position, the imaginary constellation's *cell radius* r and orientation θ.

Once the nearest benchmark position (x_i^p, y_i^p) is located, node i £rst checks whether the message sequence number is outdated or if (x_i^p, y_i^p) is identical with x_j^p, y_j^p, the benchmark position indicated in the broadcast message i receives from node j. Only when the two conditions are not true will node i mark itself as a relay node candidate and reformulate the broadcast message as indicated in Figure 3(c).

When a relay node reformulates the broadcast message, the associated benchmark position, instead of it own location, is encapsulated and relayed to its neighbors. Thus each node actually takes the imaginary constellation as its reference, which effectively avoids problem of skewness propagation (skewness of the actual constellation formed by relay nodes compared to the imaginary constellation) incurred due to limited node density.

2) Relay Node Election: The primary purpose of the "relay node election" function is to elect a relay node from all candidates that are identi£ed by the previous function component. Once being identi£ed as a relay node candidate, node i starts a deferring timer with the initial value $\mathcal{T}_i$ as:

$$\mathcal{T}_i = \mathcal{F}(d_i) \tag{1}$$

where $\mathcal{F}()$ can be any increasing function and d_i is the distance from node i to its associated benchmark position. Node i sends out the broadcast message only when following conditions are true:

1) i does not hear any other candidates relaying the same message before its timer expires;
2) As shown in Figure 1, each relay node has three neighbor nodes that are also relay nodes. i relay the message only when it does not hear all of its 3 neighbor relay nodes relay the same message for their corresponding benchmark positions.

III. Performance Analysis

In the following sections we present the analysis regarding DMTB's message complexity, time complexity, the broadcast interference and the *cell radius* with different node densities.

A. Message Complexity

De£nition The broadcast algorithm's *message complexity* is de£ned as the number of re-broadcast occurrences during each broadcast event with respect to the total number of nodes present in the network.

De£nition Denote a graph as $G = (V, E)$. An *independent set* of a graph G is a subset of the vertices such that no two vertices in the subset represent an edge of G. Let opt denote the size of any MCDS.

The following lemma is proved in [7].

Lemma 3.1: The size of any independent set in a unit-disk graph $G = (V, E)$ is at most $4 \cdot opt + 1$.

Since *opt* poses the lower bound for the size of the relay node set, we will evaluate DMTB's message complexity through its performance ratio, de£ned as the ratio of DMTB's message complexity to that of any MCDS algorithm.

Theorem 3.2: The performance ratio of DMTB is within 8 of the global optimum.

Proof: As described in previous sections, relay nodes form a constellation as shown in Figure 4. Based on the de£nition mentioned above, all solid nodes, which is exactly

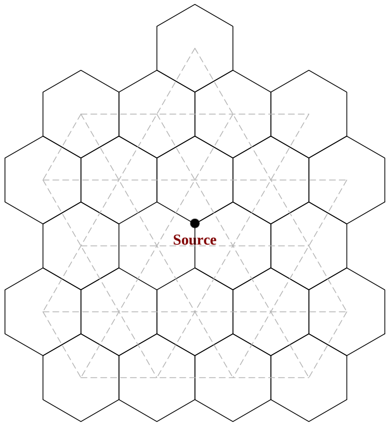

Fig. 1. DMTB's broadcast reference constellation

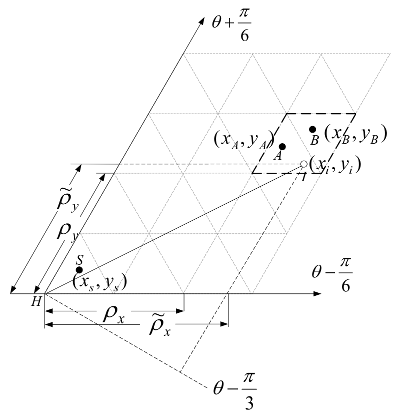

Fig. 2. A node £nds its corresponding benchmark position

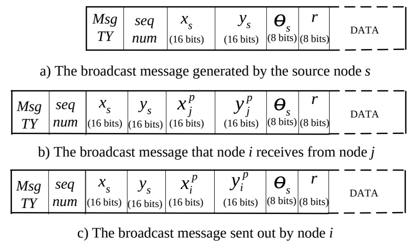

Fig. 3. Message formats utilized by the constellation based broadcast protocol

half the amount of all nodes, form an independent set. Thus, the number of solid nodes is at most $4 \cdot opt + 1$. Similarly the number of hollow nodes is also at most $4 \cdot opt + 1$. This proves that the number of relay nodes selected by our protocol is at most $8 \cdot opt + 2$. ■

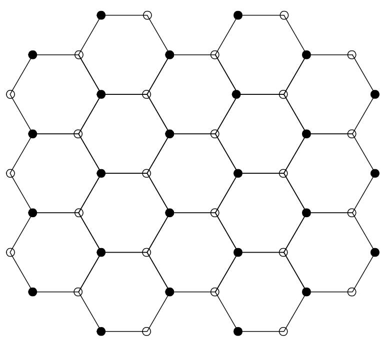

Fig. 4. DMTB's broadcast reference constellation

B. MAC Layer Interference

In the ideal scenario where a node can be found exactly at each of the benchmark positions, we have following theorem:

Theorem 3.3: In a single DMTB broadcast, at least 50%-75% of the relay nodes will not experience collisions when receiving the broadcast message.

Proof: In each broadcast event, there exists a conservation law: the number of messages received at all nodes equals the number of messages sent out from all nodes. This is because each node only relays the message at most once. In our broadcast constellation, each relay node has three neighbors that are also relay nodes. Figure 5 shows three message sending/receiving scenarios:

1) Node u receives the message from 1 neighbor and relays it to 2 other neighbors;
2) Node v receives the message from 2 neighbors and relays it to 1 neighbor;
3) Node w receives the message from 3 neighbors. It does not relay the message anymore.

Denote the fraction of the nodes that belong to each of the three types of nodes by $N(u), N(v)$ and $N(w)$ respectively

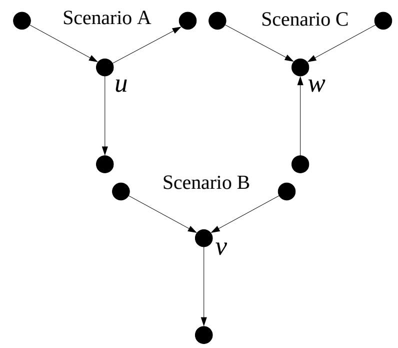

Fig. 5. Three interference scenarios

(with $N(u) + N(v) + N(w) = 1$). We have:

$$N(u) + 2N(v) + 3N(w) = 2N(u) + N(v) \qquad (2)$$

From the equation above we can get: $0.5 \leq min(N(u)) \leq 0.75$, which means that in the ideal scenario, at least 50%-75% of relay nodes receive the broadcast message once, and thus experience no collisions. ■

C. Scalability of DMTB

We have the following theorem on DMTB's scalability:

Theorem 3.4: The expected number of relay nodes employed in a single DMTB broadcast is estimated as $\frac{4 \cdot \mathcal{A}}{3\sqrt{3} \cdot r^2}$. Denoting the node density by λ and the theoretical number of relay nodes by $\mathcal{N}$, we have:

$$\lim_{\lambda \to \infty} \mathcal{N} \leq \frac{4 \cdot \mathcal{A}}{3\sqrt{3} \cdot 250^2}$$

Proof: If we denote the broadcast constellation *cell radius* by r, each hexagon's area is $A_h = \frac{3\sqrt{3}r^2}{2}$. Given a network with $\mathcal{A}$ as its area and λ as the node density, the number of hexagons needed to tile the area is $\frac{2A}{3\sqrt{3}r^2}$. As shown in Figure 4, two extra relay nodes are needed to expand each hexagon. Thus, the number of relay nodes needed by DMTB is estimated as $\frac{4 \cdot \mathcal{A}}{3\sqrt{3} \cdot r^2}$. When the node density exceeds a certain threshold and goes to in£nity, the constellation *cell radius* can be set as equal as the transmission range, 250m. Thus the theoretical number of relay nodes is bounded by $\frac{4 \cdot \mathcal{A}}{3\sqrt{3} \cdot 250^2}$ ■

IV. Simulation Results

In this section we present the simulation results. The proposed broadcast method is simulated using ns2.27. IEEE 802.11 is assumed as the MAC layer protocol. If not stated otherwise, nodes are initially uniformly deployed in the concerned areas. The transmission range of each node is 250m, and the broadcast message payload is 100 bytes. The simulation time is 1000s and broadcast messages are generated at random sources every 5 seconds. All nodes are mobile.

The mobility model used in the simulations is the "Random Direction Model" [8]. In this model, a node travels in a pre-picked random direction and a random speed until it reaches the area boundary, where it chooses a different direction and speed to continue moving. With a node's average moving speed denoted by V_{avg}, each node's speed is randomly chosen between 0 and $2V_{avg}$.

1) Broadcast Effectiveness/Ef£ciency vs. Node Mobility: We verify our broadcast protocol's effectiveness/ef£ciency and compare it with the protocol proposed in [9], which we refer to as Mobility Management (MM) in the £gures. Figure 6 presents the DMTB and MM's broadcast message delivery rate under different average node moving speeds. It can be seen that the delivery rate of DMTB stays well above 95% in both node density scenarios, even when the node average speed is as high as $160m/s$. The simulation results for MM protocol are consistent with the evaluation results from [9] and its delivery rate drops signi£cantly when the nodes' speed increases. Although the broadcast delivery rate of MM can be greatly improved with a large buffer zone (100m in the simulation), Figure 7 shows that this is indeed achieved at the cost of much more relay nodes.

2) Collision vs. Node Mobility: As indicated previously, our protocol greatly alleviates the broadcast collision. As can be seen from Figure 8, the occurrence rate stays fairly low. Collision occurrences of MM is also observed. Unlike DMTB, The collision of MM intensi£es as the node density increases.

3) Broadcast End-to-end Delay vs. Node Mobility: In Fig. 9, we observe the end-to-end delay in networks of different node average speeds and different node densities, (with the delivery rates in Fig. 6 and 7). Here $\mathcal{F}(d_i)$ is a randomly picked value between $[0, 10us \cdot d_i]$ (10us is picked since it is the typical slot time of IEEE 802.11), where d_i is the distance of the relay node i from its benchmark position. The end-to-end delay stays around 10ms even when the node density is relatively low and is not affected much when the node average speed varies signi£cantly (from 20m/s to 160m/s).

4) Energy Coef£cient of Variance vs. Node Mobility: From Figure 10 we can see that the system CV is fairly small for different node densities, and more importantly, it stays roughly the same as the node average speed changes from 20m/s to 160m/s. Again, this is attributed to the constellation greatly helps even the energy consumption across the network.

5) Protocol Robustness: To verify the protocol's robustness, we simulated broadcasting in a 2500m $\times$ 2500m area shown in Fig. 11. The node density is 1.5×10^{-4}, and static nodes are uniformly distributed in the area except the subarea, where no nodes are present, emulating node failures or a network area of irregular shape. Source nodes are randomly picked in each broadcast and 100 broadcast messages are sent during the simulation. With non-relay nodes denoted by "·" and relay nodes by "*", Fig. 11 shows a snapshot of the relay node distribution for one broadcast event. The delivery rate was observed to be 100%. This veri£es that DMTB is robust against node failures or sleeping nodes and ¤exible enough to be applied in network areas of irregular shapes.

V. Conclusion

In this paper we presented a cross-layer designed, imaginary constellation based broadcast protocol in mobile ad-hoc networks. The protocol has low overhead and its performance is guaranteed to be bound to be within a constant of the optimum (MCDS). The procedure of choosing the relay node for each benchmark position is probabilistic which helps achieve energy balance and protocols resilience while accommodating node mobility. Thorough analysis and extensive simulations are presented to address and verify DMTB's performance.

References

[1] D. Kim and N. F. Maxemchuk, "A Comparison of Flooding and Random Routing in Mobile Ad Hoc Networks," *3rd New York Metro Area Networking Workshop (NYMAN 2003)*, New York, New York, Sep. 2003.

[2] M. Garey and D. Johnson, *Computers and Intractability - A Guide to the Theory of NP-Completeness*, W. H. Freeman, San Francisco CA, 1979.

[3] N. Gupta., D. Manjunath, "Gossiping in multihop radio networks," *Personal Wireless Communication, 1999 IEEE International Conference on*, pp. 78-82, Feb. 1999.

[4] Z. Haas, J. Halpern, and L. Li, "Gossip based ad hoc routing," *In Proc. of IEEE INFOCOM*, New York, New York, June 2002.

[5] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, "The broadcast storm problem in a mobile ad hoc network,", *Proc. of ACM/IEEE MOBICOM'99*, pp. 151-162, Seattle, Washington, Aug. 1999.

[6] V. K. Paruchuri, A. Durresi, D. S. Dash, R. Jain, "Optimal Flooding Protocol for Routing in Ad-hoc Networks", *IEEE Wireless Communications and Networking Conference*, New Orleans, Louisiana, Mar. 2003.

[7] P. J. Wan, K. M. Alzoubi, O. Frieder "Distributed Construction of Connected Dominating Set in Wireless Ad Hoc Networks," *Proceedings of INFOCOM 2002*, New York, New York, June 2002.

[8] T. Camp, J. Boleng and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research," *Wireless Communication & Mobile Computing*, vol. 2, no. 5, pp.483-502, 2002.

[9] J. Wu and F. Dai, "Mobility Management and Its Applications in Ef£cient Broadcasting in Mobile Ad Hoc Networks," *INFOCOM 2004*, Hong Kong, March 7-11, 2004.

[10] F. Li and K. Wu, "Reliable, Distributed and Energy-Ef£cient Broadcasting in Multi-hop Mobile Ad Hoc Networks," *Proceedings of IEEE LCN*, pp. 761-769, Nov. 6th-8th 2002.

[11] P. J. Wan, G. Calinescu, X. Y. Li, O. Frieder, "Minimum-Energy Broadcast Routing in Static Ad Hoc Wireless Networks," *IEEE INFOCOM*, Tel Aviv, Israel, March 2000.

[12] A. K. Das, R. J. Marks, M. El-Sharkawi, P. Arabshahi, A. Gray, "Minimum Power Broadcast Trees for Wireless Networks: Integer Programming Formulations," *INFOCOM 2003* San Francisco, March 30-April 3, 2003.

Appendix I
Proof of the Plane Tiling Theorem

Proof: Let m denote the number of vertices of a m-polygon and n the number of m-polygons needed to tile 2π degree. We have the following equations:

$$\begin{aligned} \frac{(m-2)n\pi}{m} &= 2\pi \\ (m-2)(n-2) &= 4 \end{aligned}$$

Since both m and n are integers, the only solution for two integers' product to be 4 is $(1,4),(2,2)$ and $(4,1)$. Thus the

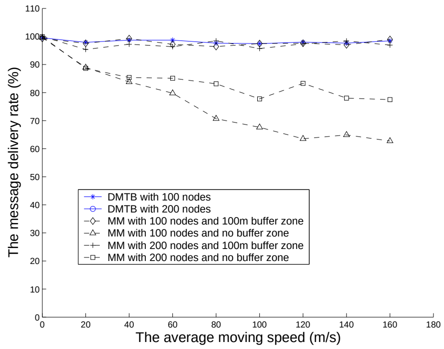

Fig. 6. The delivery rate with different node average speeds

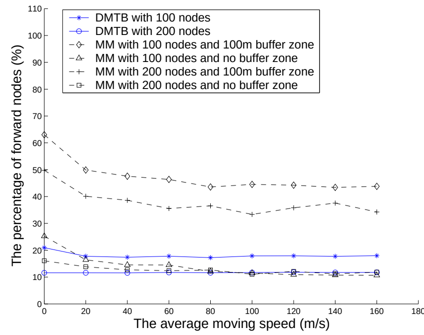

Fig. 7. The amount of forwarding nodes with different node average speeds

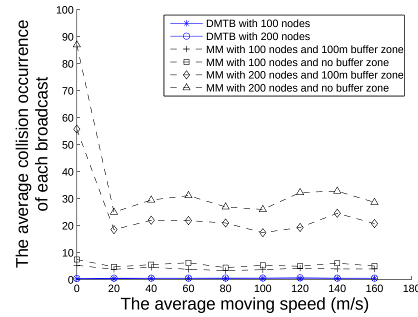

Fig. 8. The average number of collision occurrences per broadcast with different node average speeds

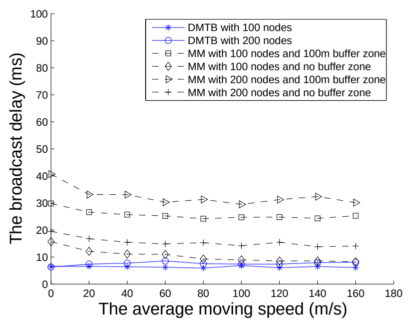

Fig. 9. The average broadcast delay with different node average speeds

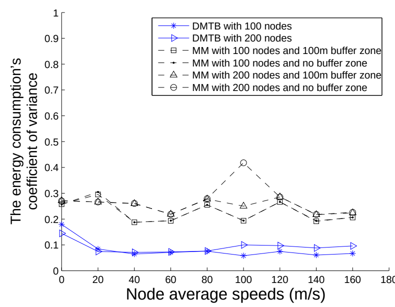

Fig. 10. The energy consumption's coef£cient of variance with different node average speeds

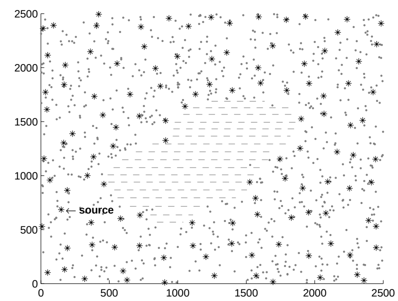

Fig. 11. Broadcast in the network area of irregular shape

three solutions of m is $3, 4, 6$, which is triangle, square or hexagon. ■

Appendix II
Benchmark Position of an Arbitrary Node

In example shown in Figure 2, to calculate node *i*'s corresponding benchmark position (x_i^p, y_i^p), we need to £nd out the *Voronoi* cell in which (x_i, y_i) resides in. We see that Voronoi cells are equilateral triangles with side length of $\sqrt{3}r$, where r is the radius of the hexagon. For any node inside a cell, its benchmark position should be the center of the triangle. We place our Voronoi tessellation in af£ne coordinates with oblique axes in the orientation of $\theta - \frac{\pi}{6}$ and $\theta + \frac{\pi}{6}$, as shown in Fig. 2. Recall that s is the source node position. Let H be the bottom-left vertex of the Voronoi cell that holds S. θ is the orientation of $\overrightarrow{HS}$, which is also the hexagon orientation embedded in the previous broadcast message.

As shown in the Figure 2, the coordinate origin and node *i*'s position as denoted as H and I respectively. Let $< \alpha, \beta >$ denote vector $\overrightarrow{HI}$, where α and β are the orthogonal projection of $\overrightarrow{HI}$ on the x and y axes, respectively:

$$\alpha = x_i - x_s + r\cos\theta \qquad \beta = y_i - y_s + r\sin\theta$$

Now we are interested in the oblique projection of vector $\overrightarrow{HI}$. In Fig. 2, it is seen that its oblique projection on the axis $\theta - \frac{\pi}{6}$ is equal to its orthogonal projection on $\theta - \frac{\pi}{3}$ divided by $\cos\frac{\pi}{6}$. Thus we can calculate this projection using the inner product:

$$\widetilde{\rho_x} = \frac{1}{\cos\frac{\pi}{6}}\left(\alpha\cos\left(\theta - \frac{\pi}{3}\right) + \beta\sin\left(\theta - \frac{\pi}{3}\right)\right)$$

Likewise, the oblique projection of $\overrightarrow{HI}$ on the axis $\theta + \frac{\pi}{6}$ is equal to its orthogonal projection on $\theta + \frac{\pi}{3}$ divided by $\cos\frac{\pi}{6}$:

$$\widetilde{\rho_y} = \frac{1}{\cos\frac{\pi}{6}}\left(\alpha\cos\left(\theta + \frac{\pi}{3}\right) + \beta\sin\left(\theta + \frac{\pi}{3}\right)\right)$$

Using the af£ne coordinates in Fig. 2, we can con£ne a node within a parallelogram composed of two adjacent Voronoi cells. For example, I is in a parallelogram which contains two cells, centered at A and B. To obtain the coordinates of A and B, we locate this parallelogram by its oblique projection:

$$\rho_x = \sqrt{3}r\left\lfloor\frac{\widetilde{\rho_x}}{\sqrt{3}r}\right\rfloor = \sqrt{3}r\left\lfloor\frac{2\alpha}{3r}\sin\left(\theta + \frac{\pi}{6}\right) - \frac{2\beta}{3r}\cos\left(\theta + \frac{\pi}{6}\right)\right\rfloor$$

$$\rho_y = \sqrt{3}r\left\lfloor\frac{\widetilde{\rho_y}}{\sqrt{3}r}\right\rfloor = \sqrt{3}r\left\lfloor\frac{2\beta}{3r}\cos\left(\theta - \frac{\pi}{6}\right) - \frac{2\alpha}{3r}\sin\left(\theta - \frac{\pi}{6}\right)\right\rfloor$$

Recall that $\sqrt{3}r$ is the side length of a Voronoi cell. Therefore the coordinates of A and B are:

$$\begin{aligned}
x_A &= x_s + \rho_x\cos\left(\theta - \frac{\pi}{6}\right) + \rho_y\cos\left(\theta + \frac{\pi}{6}\right)\\
y_A &= y_s + \rho_x\sin\left(\theta - \frac{\pi}{6}\right) + \rho_y\sin\left(\theta + \frac{\pi}{6}\right)\\
x_B &= x_A + r\cos\theta\\
y_B &= y_A + r\sin\theta
\end{aligned}$$

A and B are two candidates for the benchmark position of I and the £nal position is the one that is closer to I. De£ne:

$$\eta = [(x_i - x_A)^2 + (y_i - y_A)^2] - [(x_i - x_B)^2 + (y_i - y_B)^2]$$

then:

$$(x_i^p, y_i^p) = \begin{cases} (x_A, y_A) & \text{if } \eta < 0 \\ (x_B, y_B) & \text{if } \eta > 0 \end{cases}$$