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QOS-ENERGY AWARE BROADCAST FOR HETEROGENEOUS WIRELESS AD HOC NETWORKS

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We present QoS Geometric Broadcast Protocol (QoS-GBP), a novel broadcasting protocol for heterogeneous wireless ad hoc networks. The growing number of multimedia applications over wireless ad hoc networks require low delay from network protocols and in particular from broadcasting. While broadcasting is a very energy-expensive protocol, it is also widely used as a building block for a variety of other network layer protocols. Therefore, reducing the energy consumption by optimizing broadcasting is a major improvement in heterogenous wireless ad hoc networks networking. QoS-GBP is a distributed algorithm where nodes make local decisions on whether to transmit based on a geometric approach. QoS-GBP enables a tradeoff among the need for neighborhood information (communication overhead) and the delay. QoS-GBP is scalable to the change in network size, node type, node density and topology. Through simulation evaluations, we show that QoS-GBP is very scalable and guarantees minimum delay.

Keywords: Broadcast, QoS, Energy aware protocols, Multimedia Applications, Wireless Ad Hoc Networks.

1 Introduction

The revolutionary advances in the wireless communication technologies are enabling the realization of wide range of heterogeneous wireless systems. Heterogeneous Ad hoc Networks consist of wireless nodes that cooperatively communicate with each other without the existence of fixed network infrastructure. Depending on different geographical topologies, the nodes are dynamically located and continuously changing their positions. The fast-changing characteristics in ad hoc networks make it difficult to discover routes between nodes. It becomes important to design efficient and reliable multihop routing protocols to discover, organize, and maintain the routes in ad hoc networks.

In contrast to most stationary computers, mobile device encounter more heterogeneous network connections. As they leave the range of one network transceiver they switch to another. In different places they may experience different network qualities. The wide range of variety of wireless technologies include WLAN, sensors, actuators, cell phone, vehicular nodes, etc.

Heterogeneous wireless networks will enable existing and new applications. For example, sensor networks [4, 3, 15, 21, 10, 34] could warn cellular users of various perils; driver information services could intelligently inform drivers about congestion, businesses and services in the vicinity of the vehicle/cell phone, and other news. Mobile commerce could extend to the realm of wireless users. Existing forms of entertainment may penetrate the mobile domain, and new forms of entertainment may emerge.

The rapid growth in interactive multimedia applications, such as video telephones, video games and TV broadcasting have resulted in spectacular advances of of multimedia wireless communication systems. While multimedia applications have specific requirements about network QoS, especially about delay, bandwidth and jitter, begin with, wireless connections are by nature significantly less stable than wired connections. Effects influencing the propagation of radio signals, such as shielding, reflection, scattering, and interference, inevitably require routing systems in ad hoc networks to be able to cope with comparatively low link communication reliability. Also, many scenarios for multimedia over ad hoc networks assume that nodes are potentially mobile.

Various types of wireless nodes might need to save energy. For example, sensor nodes in general are extremely small, low-cost, low energy that possess sensing, signal processing and wireless communication capabilities. Sensors usually gather information about the physical world. Actor nodes are nodes capable taking decisions and then perform appropriate actions. An example of actor nodes are robots able of sensing, communicating and performing actions. Actor nodes in general are equipped with larger energy sources than sensors. Heterogeneous ad-hoc wireless networks of large numbers of such inexpensive but less reliable and accurate sensors combined with few actors can be used in a wide variety of commercial and military applications such as target tracking, security, environmental monitoring and system control.

In wireless sensor networks, it is critically important to save energy. Battery-power is typically a scarce and expensive resource in wireless devices. Current research on routing in wireless sensor networks mostly focused on protocols that are energy aware to maximize the lifetime of the network, are scalable to accommodate a large number of sensor nodes, and are tolerant to sensor damage and battery exhaustion [6, 8, 23, 37, 38, 39]. We have proposed recently an integrated power management and routing routing protocol [28] that enables tradeoffs between energy consumption and latency.

Network broadcasting is the process in which one node sends a packet to all other nodes in the network. Many applications as well as various unicast routing protocols use broadcasting or a derivation of it. Applications of broadcasting include location discovery, establishing routes and querying. Broadcasting can also be used to discover multiple paths between a given pair of nodes. Many routing protocols propose to use localized flooding for route maintenance.

Also, once the approximate location of a node is known, flooding restricted to an area limited around that location can be used to discover the exact location. In most of the instances the broadcast functionality is done using flooding, in which each node will be required to rebroadcast the packet whenever it receives the packet for the first time. Flooding generates many redundant transmissions, which may cause a more serious *broadcast storm problem*

[26]. Consequently flooding is a very energy and bandwidth expensive functionality in sensor networks.

Recently, a number of research groups have proposed more efficient broadcasting techniques. Centralized broadcasting schemes are presented in [5, 16, 17]. Algorithms in [25, 31, 33] utilize neighborhood information to reduce redundant messages in a Mobile Ad Hoc Network. Schemes in [20, 35, 22] deal with disseminating data in sensor networks.

In [13] we have introduced Broadcast Protocol Sensor (BPS) networks, explicitly designed for wireless sensor networks. While reducing energy consumption was the primary goal in our design, our protocol achieves good scalability and low latency. To achieve the primary goal of energy efficiency, we reduce the number of retransmissions by using a geometric approach. We assume that each node knows its location, which also is a requirement for various other routing protocols, sensing, target tracking and other applications. Various techniques like GPS [12], Time Difference of Arrival [32], Angle of Arrival [27] and Received Signal Strength Indicator [7] have been proposed to enable a node to discern its relative location. Recently, a range-free cost-effective solutions [19] has been proposed for the same problem.

QoS-GBP presented here is an extension of our previous work [13],[14]. Due to the nature of the wireless communication and unpredictable traffic pattern, it is infeasible to guarantee hard real-time constrains, therefore, we have designed QoS-GBP to provide probabilistic guarantee for timing constraints. While the protocol proposed in [13] guarantees the minimum overhead at the cost of some delay, QoS-GBP offers a tradeoff between the delay and the communication overhead.

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 presents a summary of our BPS protocol. Section 4 presents QoS Geometric Broadcast Protocol . Section 5 describes our simulation model and discusses the simulation results. Section 6 concludes the paper.

2 Related work

Network-wide broadcast is an essential feature for wireless networks. The simplest method for broadcast service is flooding. Its advantages are its simplicity and reachability. However, for a single broadcast, flooding generates abundant retransmissions resulting in battery power and bandwidth waste. Also, the re-transmissions of close nodes are likely to happen at the same time. As a result, flooding quickly leads to message collisions and channel contention. This is known as the broadcast storm problem [26].

The solutions presented in [5, 16, 17] are deterministic and guarantee a bounded delay on message delivery, but the requirement that each node must know the entire network topology is a strong condition, impractical to maintain in wireless networks. Several broadcast protocols that do not require the knowledge of the entire network topology have been proposed. In a counter-based scheme [26], a node does not retransmit if it overhears the same message from its neighbors for more than a prefixed number of times and in a distance-based scheme [26], a node discards its retransmission if it overhears a neighbor within a distance threshold re-transmitting the same message.

Source Based Algorithm [29], Dominant Pruning [25], Multipoint Relaying [31], Ad Hoc Broadcast Protocol [30], Lightweight and Efficient Network-Wide Broadcast Protocol [33] utilize two-hop neighbor knowledge to reduce number of transmissions. But in large scale sensor networks, especially with high densities, the two-hop neighbor knowledge might impose very high memory overhead. A good classification and comparison of most of the proposed protocols is presented in [36].

In Gossip-based routing [18], a node probabilistically forwards a packet so as to control the spreading of the packet through the network; the probability typically being around 0.65. Though, this simple mechanism reduces the number of redundant transmissions, there is still a lot of scope for improvement.

Several data dissemination protocols [20, 35, 22] have been proposed for sensor networks to disseminate data to interested sensors rather than all sensors. A broadcast protocol is presented in [11] for regular grid-like sensor networks.

In this paper we propose a new QoS and energy aware broadcast protocol base on a geometric approach. Our new protocol, QoS-GBP offers tradeoff among delay, energy consumption and scalability. The scalability of QoS-GBP is illustrated through simulations, in which the number of retransmitting nodes gradually decreases as the number of nodes in the network increases.

3 Geometric Broadcast Protocol (GBP)

In this Section we give a short presentation of GBP [13]. GBP was designed as a modification to *The Covering Problem* can be stated as follows: "What is the minimum number of circles required to completely cover a given two-dimensional space." Kershner [24] showed that no arrangement of circles could cover the plane more efficiently than the hexagonal lattice arrangement. Initially, the whole space is covered with regular hexagons, whose each side is R and then, circles are drawn to circumscribe them, as shown in Fig. 1.

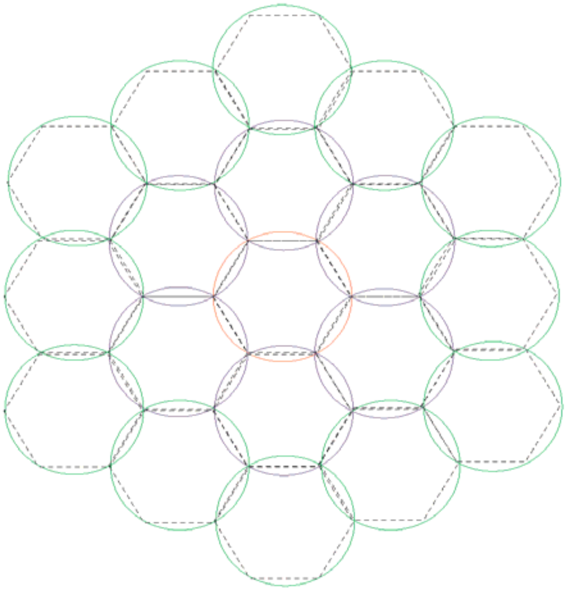

Fig. 1. Covering a plane with circles in an efficient way.

We have modified the covering problem to the following algorithm, initially explained for ideal conditions. The area to be covered with radio signal is portioned into hexagons. The communication range of nodes determines the hexagons' length of sides. The Source S is at the center of one of the hexagons. In an ideal network, all other transmission nodes are at, as shown in Fig. 2. We will call the vertices of the hexagons strategic locations. The broadcasted packets are propagated along the sides of the hexagons. Any active node located inside a hexagon is reachable from at least one of the vertex nodes of the hexagon. Of course, in real conditions, it is impractical to assume that active nodes are located at the hexagons' vertices. Thus, if the active neighbor nodes are not in the optimal strategy locations, the coverage figure will be distorted; moreover, the distortion effect may propagate, as shown in Fig. 3. A simple solution is to select the nearest active node to the supposed vertex.

It should also be observed that a node could receive a packet more than once - from different directions and from different nodes, each node specifying different optimal strategic location (because of distortion). This may cause two nodes very close to each other to retransmit. We propose to avoid these transmissions by having a node keep track of its distance dm to the nearest node that has retransmitted the packet and to have a node retransmit only when its distance to the nearest transmitting node is greater than a threshold Th.

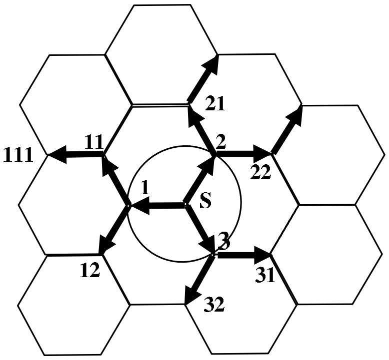

Fig. 2. Our Solution for the Modified-Covering Problem.

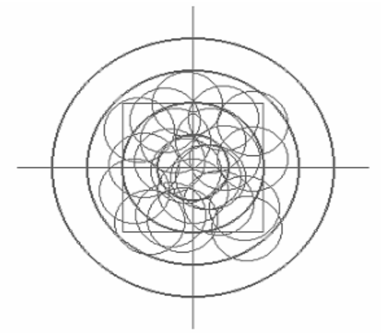

Fig. 3. GBP for real conditions.

The degree of distortion, as expected, is high in networks with low density, as there might not be any nodes close to strategic locations. As the density increases, the distortion decreases because the probability of finding a node closer to the strategic location increases. Therefore, the higher the density, the better the performance of GBP, because it will operate closer to the ideal case.

In [13] we have shown through simulations that our GBP protocol outperforms other broadcasting protocols. We would like to stress that we have tested GBP in real conditions, in which the coverage figure becomes distorted considerably, as shown in Fig. 3 and in most of the cases no node exists at the strategic location.

4 QoS Geometric Broadcast Protocol (QoS-GBP)

In this section, we present the QoS Geometric Broadcast Protocol (QoS-GBP) for heterogeneous wireless ad hoc networks.

We assume that each node has knowledge of its one-hop neighbors. Thus once a node decides to retransmit a broadcast packet, the node not only calculates the next strategic locations, but also computes the nearest nodes to those strategic locations and includes those node *ids* in the broadcast packet. If nodes with different transmission range are present in the one-hop neighborhood, the node that will cover more area will be selected as the next transmission node. Whenever a node receives a broadcast packet, it checks the packet if its *id* is listed in the header. If it is, then it repeats the procedure.

Algorithm

Each broadcast packet contains two location fields, L_1 and L_2 in its header and a list of nodes close to strategic locations. Whenever a node transmits a broadcast packet, it sets L_1 to the location of the node from which it received the packet and sets L_2 to its own location. The Source Node S sets both L_1 and L_2 to its location (S_X, S_Y) and transmits the packet.

1. Upon the reception of a broadcast packet, an active node M discards the packet if M has transmitted the packet earlier, or if a node which is very close has already transmitted this packet, i.e., if $d_m < Th$. M continues the algorithm if it is part of the list of nodes close to the strategic location.

2. If the packet is not discarded, M finds the nearest vertex V (for example node 1 in Fig. 2.) of a hexagon with $(S_X,\ S_Y)$ as its center coordinates and with $(S_X + R,\ S_Y)$ as one of its vertices. M also computes the nearest nodes to those strategic locations and includes those node *ids* in the broadcast packet. It computes its distance l from the received closest node to its strategic and then delays the packet rebroadcast by a delay d given by $d = l/R$.

3. After the delay d elapses, M determines if it has received the same packet again and if the packet can be discarded (for the same reasons mentioned above). In case M is the closest node to its strategic location, there is no delay in retransmission. If for some reason the closest node to the strategic location does not retransmit, delaying enables the selection of an active node that successfully received the packet and is the nest closest to the corresponding strategic location. In the case that the packet cannot be discarded, M retransmits.

The purpose of having the threshold *Th* is to prevent two active nodes that are very close to each other from transmitting, thus reducing the redundancy. The key factors depending on *Th* are the number of transmissions and the delivery ratio. As *Th* increases, the number of transmissions decreases. This happens because when *Th* increases, the minimum distance between any two transmitting nodes increases. This in turn implies that additional area covered increases, and hence, the number of transmissions needed for covering entire network decreases. The higher the number of transmissions, the higher is the redundancy, and therefore the greater is the probability that a node receives broadcast. Therefore, for higher delivery ratios, lower *Th* is preferred. Through extensive simulations we have found that for a threshold value of $Th = 0.35 * R$, a delivery ratio of around 98% is achieved and for $Th = 0.4 * R$, the delivery ratio is close to 95%. However, when $Th = 0.45 * R$, the delivery ratio falls to around 90%. This is understandable, because with the increase in threshold value, the number of retransmitting nodes decreases. For all further simulations, we use threshold value of $Th = 0.35 * R$.

The computational complexity of QoS-GBP is negligible; when compared to flooding, the major additional computation is finding the node's distance to the nearest optimal point according to the modified covering problem, which can be easily computed. The only bandwidth overhead due to QoS-GBP is because of addition of new header fields to carry location information of several nodes which is not significant.

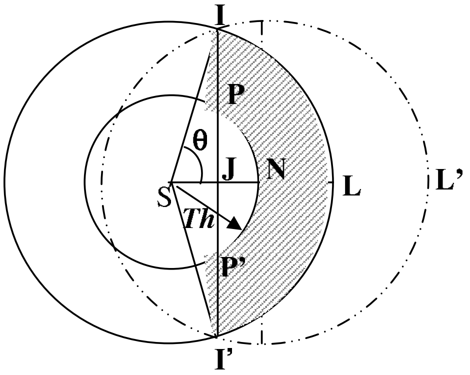

Fig. 4. A scenario illustrating effect of *Th*.

Effect of Threshold *Th*

The purpose of having Threshold is to prevent two nodes that are very close to each other from transmitting, thus reducing the redundancy. The key factors affecting *Th* are number of transmissions and delivery ratio.

Number of transmissions: As *Th* increases, the number of transmissions decreases. This is because, at high *Th* values, the minimum distance between any two transmitting nodes is more. This in turn implies that additional area covered is higher and hence number of transmissions needed for covering the entire network is lesser.

Delivery Ratio: It is the percentage of nodes that received the broadcast. More the number of transmissions more is the redundancy and hence more is the probability that a node receives the broadcast. So, for higher delivery ratios, lower *Th* are preferred.

To elaborate, consider Fig. 4. For simplicity, consider transmission range as unity. For a given Th, the additional area covered due to a transmission by a neighbor of S is at least $\Delta_{ILI'L'}$, area of $ILI'L'$.

$$\Delta_{ILI'L'} = \pi - 2 * \Delta_{JILI'} = \pi - 2\theta + Th * \sin\theta \tag{1}$$

where, $\theta = \cos^{-1}(Th/2)$

Now, for higher *Th* values, $\Delta_{ILI'L'}$ is high and hence lesser transmissions are enough to cover the region. But, at the same time, if *Th* is high, the number of potential neighbors that could retransmit the message is less. To illustrate, consider the shaded region $IPNP'I'L$. At high *Th* values, this area is less and hence the probability that some node exists in this area is also less. Thus, at high *Th* values there might not be any transmission corresponding to the strategic location *L*. This might result in some nodes not receiving the broadcast.

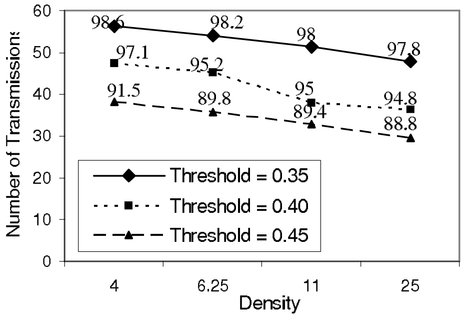

Fig. 5. Effect of *Th* on the performance of QoS-GBP. Network size = $6RX6R$.

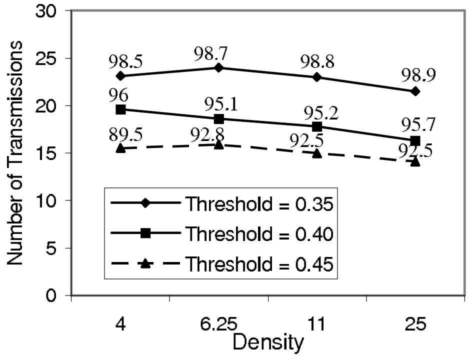

Fig. 6. Effect of *Th* on the performance of QoS-GBP. Network size = $6RX6R$.

We illustrate the tradeoff on the value of *Th*, by using ns-2 simulations. Figs. 5 and 6 show the simulation results for threshold values of 0.35R, 0.40R and 0.45R. Apart from the number of transmissions in each case, the delivery ratio in percentage for each case is indicated at each data point. Delivery Ratio is the average number of nodes that receive the message to the total number of nodes in the network. Fig. 5 is for a network size of $6R * 6R$ and Fig. 6 is for a network of size $4R * 4R$.

For a threshold value of $Th = 0.35R$, a delivery ratio of around 98% is achieved and for $Th = 0.4R$, the delivery ratio is around 95%. But, for $Th = 0.45R$, the delivery ratio falls to around 90%. This is understandable, because with the increase in threshold value, number of retransmitting nodes decrease.

For all further simulations, we use threshold value of $Th = 0.4R$ and for each simulation case, we present the minimum and maximum delivery ratio, instead of presenting the delivery ratio for each for each data point.

5 Performance Evaluation

We evaluated the performance of our protocol by using ns-2 simulator [2].

We used the following metrics to evaluate the performance of QoS-GBP:

- *Scalability* is measured by the number of retransmissions needed to cover a given network. *Scalability* is a major evaluation metric for networks in general, but it is crucial especially for dense wireless networks. One of the main advantages of our solution is its excellent *Scalability.*

- *Delivery Ratio* measures the percentage of nodes that have received a given broadcast message. We would like that all nodes receive the broadcast.

- *Time to Broadcast* measures the time needed to finish the broadcast of a given message over the whole network. Especially for QoS applications we would like the *Time to Broadcast* to be minimal.

Besides the above metrics, we evaluate our protocol by measuring the performance improvement/gain that other protocols can provide when QoS-GBP is included in them.

In Fig. 7 we show the comparison results among QoS-GBP [13], flooding and GOSSIP [18]. Not only is QoS-GBP significatively more scalable than flooding and GOSSIP, but as the density increases the number of transmissions in QoS-GBP decreases. QoS-GBP, when compared to flooding, uses up to 65% to 90% fewer messages depending on the density of the network.

Fig. 8 compares the performance in terms of number of retransmissions of QoS-GBP and GBP for a 8×8 network with varying densities. In ideal MAC conditions, the performance of the protocols should be same because same set of nodes will be selected to retransmit the broadcast packet. We observed this to be true. As shown in Fig. 8, the performance is almost same for both the protocols.

QoS-GPB can be used as a broadcasting protocol on its own or it can be included in other routing protocols in which broadcasting is involved. For example, QoS-GBP can be used as a module inside other network protocols by improving their performance. In Fig. 9 we show some preliminary results about the performance improvements of Two-tier Data Dissemination (TTDD) Model for Large-scale Wireless Sensor Networks [40] when it uses QoS-GBP. It can be seen that even for modest cell sizes of $3R \times 3R$ and a density of 6 nodes per $R \times R$, there is a gain of over 40 transmissions per query. At higher densities the gain is much more significant.

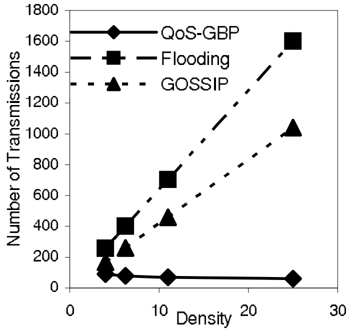

Fig. 7. Comparison among QoS-GBP, Flooding and GOSSIP.

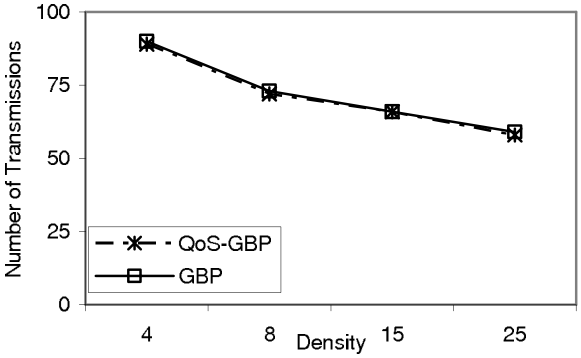

Fig. 8. Number of transmissions vs. network density.

TTDD [40] provides scalable and efficient data delivery to multiple, mobile sinks. Each data source in TTDD proactively constructs a grid structure, which enables mobile sinks to continuously receive data on the move by flooding queries within a local cell only. TTDD's design exploits the fact that sensors are stationary and location-aware to construct and maintain the grid infrastructure with low overhead.

The impact of sink's mobility is dealt by flooding a region confined to the local cell. Though the flooded region is very small when compared to the size of the network, it can be still very significant especially when cell size is large or when network density is high. For instance, the authors in [40] propose a cell size up to $1000m \times 1000m$. Thus, when cell size is $3R \times 3R$ to $4R \times 4R$, for even modest densities of 8 sensors/R2 there would be at least 72 to 128 transmissions due to flooding in one cell.

We incorporate QoS-GBP within TTDD such that a query is broadcasted within a cell through QoS-GBP mechanism rather than by flooding. QoS-GBP requires approximately constant number of transmissions to cover a given cell. For instance it requires less than 10 and 18 transmissions to cover $3R \times 3R$ and $4R \times 4R$ regions respectively.

The communication overhead of TTDD [40] is as follows:

$$Co_{TTDD} = Nl + \frac{4N}{\sqrt{n}}l + kmnl + kc(ml + d)\sqrt{2N} \tag{2}$$

The parameters are as described in [40]. The product $n \times l$ in the third term in the right hand side of the equation corresponds to the number of transmissions resulting due to flooding. With QoS-GBP, we can replace this term by C. C is the number of transmissions with QoS-GBP. Thus, communication overhead can be represented as follows:

$$Co_{TTDD-(QOS-GBP)} = Nl + \frac{4N}{\sqrt{n}}l + kmC + kc(ml + d)\sqrt{2N} \tag{3}$$

The communication gain is thus $km(nl - C)$. Fig. 9 shows the performance gain in number of transmissions per query in TTDD with QoS-GBP over pure TTDD for varying densities and cell sizes. It can be seen that even for modest cell sizes of $3R \times 3R$ and a density of 6 nodes per $R \times R$, there is a gain of over 40 transmissions per query. At higher densities the gain is much more significant.

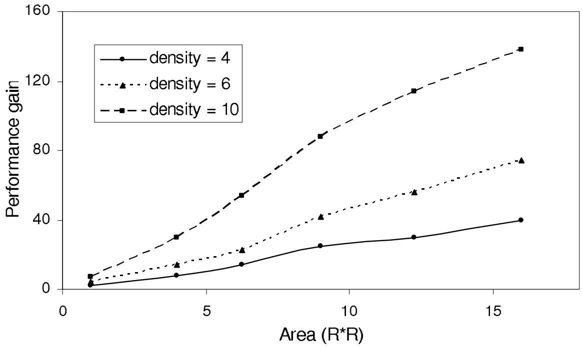

Fig. 9. Communication Gain when using TTDD with QoS-GBP.

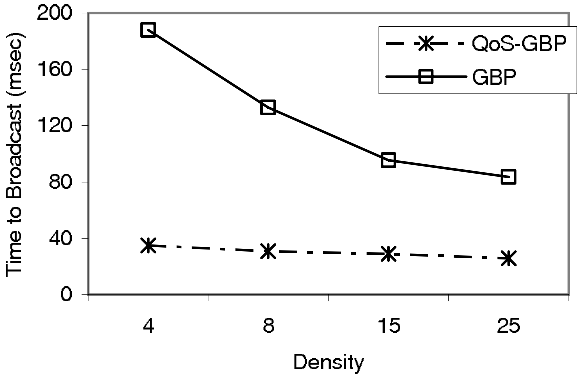

Fig. 10. Time to broadcast vs. density.

Fig. 10 shows the average time taken to finish the broadcast process for both GBP and

QoS-GBP. The time is measured from the moment the broadcast message is initiated by the source node till the moment the last broadcast message was transmitted in the network.

In case of QoS-GBP, the broadcast time slightly decreases as density increases. The reason is that at higher densities, the approximation of the ideal solution is higher, resulting in lesser number of transmissions and also shorter maximum hop-length to reach any node in the network. This results in lower broadcast time at higher densities. The broadcast time for GBP decreases significantly as density increases. At lower densities, as shown in Fig. 10, the delay per hop due to the counter is higher and this delay decreases rapidly as density increases. Thus, the broadcast time significantly decreases at higher densities.

In fact, Fig. 10 shows a direct tradeoff between latency and energy. QoS-GBP is quick in performing the broadcast mechanism, but at the cost of hello messages to maintain up-to-date neighbor knowledge. At the same time, GBP uses almost same number of retransmissions to perform the broadcasting but it takes longer duration to finish the process. The advantage is that there is no need of neighbor knowledge which implies that there is no need for hello messages.

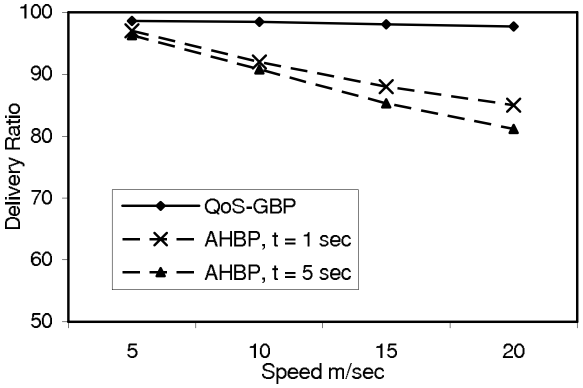

Fig. 11. Comparison between QoS-GBP and AHBP for mobile networks.

We also compare the performance in the scenario of mobile nodes. We use the Random Walk Mobility Model [9] with zero pause time and maximum speed 20 m/s. For such scenario, We compare QoS-GBP to Ad Hoc Broadcast Protocol (AHBP) [30] as AHBP is one of the protocols (SBA [29] being the other) that approximates MCDS fairly [36]. A wireless network of different physical areas and different shapes with different number of nodes were simulated.

In Fig. 12 we present the comparison results between QoS-GBP and GBP for mobile nodes. We observe that the performance of QoS-GBP deteriorates as the speed increases. This is because at higher speeds the chances that the neighbor information at a node is outdated is higher. Interestingly, GBP maintains its performance even in mobile networks showing that its performance is indeed independent of neighbor locations. We considered hello interval of 15 seconds for these simulations. Therefore, the user might use QoS-GBP or GBP depending on network conditions. If the speeds of nodes are not very high, QoS-GBP guaranties lower delays, but for higher nodes' speeds, GBP performs slightly better.

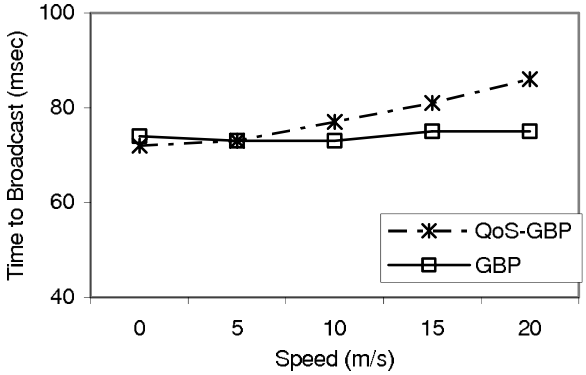

Fig. 12. Time to broadcast vs. speed of nodes.

6 Conclusion

We presented QoS Geometric Broadcast Protocol (QoS-GBP), a novel protocol that can be used by applications with QoS requirements over heterogeneous Wireless Ad Hoc Networks.

QoS-GBP is a distributed algorithm where nodes make local decisions on whether to transmit based on a geometric approach. QoS-GBP enables tradeoffs between the broadcast delay and communication overhead (hello messages needed to keep neighbor information).

QoS-GBP is scalable to the change in network size, node type, node density and topology. Through simulation evaluations, we showed that QoS-GBP is very scalable and guarantees low broadcast delays.

QoS-GBP can be used as a broadcast protocol or it can be used as a building block by other routing protocols.

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