Addressing by Beacon Coordinates using Molecular Communication

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Abstract—**A transmitter nanomachine performs molecular communication to transmit information to a receiver nanomachine using molecules (e.g. calcium ions, DNA) as the transmission medium. Existing approaches use the type of molecule to address receivers within a local broadcast area. In the proposed system, molecular beacons provide distance measurements using molecular communication to establish a coordinate system (e.g. molecular beacons form a concentration gradient using a few types of beacon molecules). Transmitters then address a receiver at a location by the distance from the receiver to each beacon. A transmitter communicates by encapsulating information into a molecular device capable of active transport and distance measurement (e.g. a bacterium performs chemotaxis to a location with the corresponding concentrations of each type of beacon molecule). This paper describes a model of the proposed system, simulation model for the example of bacterial chemotaxis, and measurement of success rate and delay.**

Keywords-Molecular communication, beacon coordinate system, location address

I. INTRODUCTION

Molecular communication is the process of transmitting information using molecules (e.g. calcium ions, peptides, DNA) as the transmission medium [1]. Molecular communication is suitable for nanomachines which are limited in size and capability and for interfacing with biological systems which perform functions controlled or influenced by molecules. A nanomachine is a device with a size in the nano- to micro-scale range. For example, a biological nanomachine may be a protein complex, a bacterium, or a cell.

A molecular communication involves: a transmitter encoding information onto molecules, the transmitter nanomachine releasing molecules into an aqueous environment, the molecules propagating through the aqueous environment, a receiver nanomachine receiving the molecules, and finally the receiver nanomachine decoding information from the molecules. Recent molecular communication research describes designs for molecular communication systems which propagate molecules through various biological processes such as diffusion, molecular motors [2][3], calcium waves [4], and bacterial chemotaxis [5]. The molecular communication systems have been modeled to evaluate their potential channel capacity and communication delays.

In many designs for molecular communication systems, receiver nanomachines are addressed using a predetermined type of molecule (e.g. type of ion, peptide, energy molecule, or DNA sequence). Several recent related work also consider a single transmitter broadcasting by molecular communication to many receivers [3][6]. This paper focuses on addressing receivers by the location of the receiver. Addressing receivers by location may increase the number of nanomachines to which a transmitter can distinctly communicate using only a single type of molecule. For example, transmitters and receivers on a surface all communicate with the same type of molecule, and the transmitter can select with which receiver to communicate by the location of the receiver. In this case, transmitters are all communicating on the same channel (i.e. the same type of molecule) but avoid interference since transmissions are directed to a location. Addressing receivers by location may also provide useful functionality for applications. It also provides an alternative interface to interact with objects at a location. For example, a self-organizing system may transport various types of molecules to specific locations to produce a pattern of molecules on a surface.

The research area of wireless networks (i.e. electronic devices transmitting over radio waves) includes system designs to transmit to wireless devices by location [7]. The location information has been used to design routing protocols and to provide additional information to interact with sensor network devices. Other research has focused on using relative locations of wireless devices to perform functions which only require location relative to other wireless devices. In [8], several wireless devices act as beacons to produce a hop-count based coordinate system. The proposed system is different from wireless networks, since the proposed system uses molecular communication to determine the location of receivers.

In the proposed molecular communication system, a relative coordinate system is established which uses distance measurements to guide molecular carriers capable of active transport to a target location. Recent research in molecular communication has described how a transmitter can communicate with a receiver by molecular communication to determine the distance between the transmitter and receiver [9].

Techniques to measure distance include the transmitter measuring propagation delay from the transmitter to the receiver, measuring the fading of concentration amplitude, or measuring the fading of frequency. If a transmitter knows the distance to several receivers, and receivers are immobile, then the distance information identifies the location of the transmitter. The vector of distances to the immobile receivers defines a coordinate system. A molecular device can move to a specific location in the coordinate system by detecting its location in the coordinate system and moving in the direction of the desired location.

Section II describes architecture and components of the proposed system. Section III describes modeling and Monte Carlo simulation of the proposed system.

II. PROPOSED SYSTEM

A. Components in the Proposed System

The proposed system establishes a coordinate system to transmit information to specific locations in the coordinate system. The coordinate system is established relative to a set of nearby beacon nanomachines, $B = (b_1, \ldots, b_n)$. A receiver is identified by a set of distances, $D = (d_1, \ldots, d_n)$, relative to each of the beacons. A transmitter nanomachine is assumed to have the set of distances, D, for the receiver to which it is communicating. Fig. 1 illustrates a receiver, three beacons, and distances measured between the beacons. The transmitter nanomachine releases a carrier, which is a molecular device capable of detecting distance and carrying information to be transmitted to the receiver. The carrier is designed to move towards specific distances from each of the beacons so that the carrier is at a location matching D. Once the carrier arrives at a location matching D, the carrier allows information to be received by any receiver it contacts.

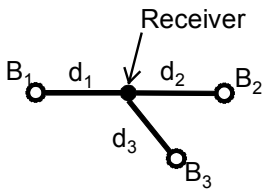

Figure 1. Positioning of a receiver by distances (d_1, d_2, d_3) relative to three beacons (B_1, B_2, B_3).

B. Beacon Coordinate System

Distance measurement techniques can be applied to establish a coordinate system. Each molecular beacon adds a distance attribute to all locations in space. In [9], the distance attribute is measured by propagation delay, fading of concentration of distance, or by fading of frequency through repeaters. In [5], a receiver produces molecules at a fixed rate resulting in a concentration gradient of a molecule and bacteria propagate towards a receiver by following the concentration gradient which corresponds to distance from the receiver. Unlike [5], the proposed system produces a new method to address receivers by a beacon coordinate system.

Bacteria can be engineered to detect specific concentrations which can correspond with a specific location in the coordinate system [10]. The proposed system requires a transmitter to dynamically modify the reaction of the carrier to each beacon. For example, the transmitter modifies carrier behavior by transferring a certain type and number of molecules into the carrier. The type of molecule is selected to increase or decrease the reaction of the bacterium to a specific type of beacon molecule (e.g., selected to modify DNA expression or protein mechanisms in the response of the bacterium to the type of beacon molecule) and the number of molecules corresponds to the desired distance to a beacon. It is also likely that the bacterium must be genetically modified so that the behavior of the bacterium is sensitive to the number of molecules transferred by the transmitter.

Fig. 2 illustrates the fixed concentration gradient which can be used to infer distance from a beacon. Since the concentration is a decreasing function, each distance from a beacon has a unique concentration. However, at a far distance from the beacon, concentration only changes a small amount over a distance. Thus, a bacterium may not precisely measure distance from the beacon when the bacterium is far from the beacon. For a beacon releasing molecules at a given rate, [5] describes the range of distances in which a bacterium can distinguish differences in concentration. The rate of release can be tuned to select which range of distances the bacterium can more precisely measure.

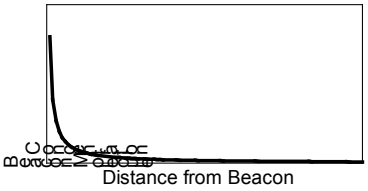

Figure 2. Steady state concentration of a type of beacon molecule decreases as the distance from the beacon producing the type beacon molecule increases.

C. Carrier movement

Since the carrier is at the micro- or nano-scale, the carrier does not have precise control over its position or movement. In nature, several types of micro-scale cells (e.g. bacteria) perform chemotaxis to move towards a location which has beneficial molecules (or away from a location with detrimental molecules) [11]. Chemotaxis functions by biasing the cell to move towards the beneficial location rather than away from the beneficial location. In the case of a bacterium, the bacterium travels in roughly the same direction over a short duration (on the order of seconds) and detects the concentration of the beneficial molecules. If the concentration of the beneficial molecules is increasing over time, the bacterium is likely to be moving towards the location with beneficial molecules, and the bacterium is more likely to continue in the same direction (i.e. run). If the concentration is decreasing over time, the bacterium is likely to be moving away, and the bacterium becomes more likely to randomize its direction (i.e. tumble).

A carrier in the proposed system applies an algorithm similar to bacterial chemotaxis to arrive at the receiver. In the

case of the natural bacterium, the bacterium measures the distance to the beneficial location by concentration of beneficial molecules. In the proposed system, the carrier can also measure its distance by distance measurement protocols [9]. To apply distance measurement protocols, the carrier adheres to a surface at a location and detects its distances, D_1, from the beacons at one location. Then, the carrier detaches from the surface, moves forward and attaches itself to a new location (assuming a carrier can maintain orientation while adhering and detaching). At the new location, the carrier detects a second set of distances, D_2. If the carrier is moving closer to the receiver the carrier continues in the same direction. If the carrier is moving away from the receiver, the carrier randomizes its direction. For example, attaching/detaching can be performed with molecular motors walking on a surface with many randomly oriented microtubules. A carrier continues walking along a microtubule if beacon concentration improves (i.e. concentration is approaching the target concentration). If concentration worsens, the carrier detaches from the microtubule, diffuses, and randomly attaches to another microtubule. Note that in the proposed system, the carrier is targeting a specific distance from each beacon, and thus, if the carrier is too close to a beacon it must move further away from the beacon.

In the case of bacterium sensing distance by a concentration gradient, the bacterium can acquire a relatively high precision concentration measurement by averaging over a period of time. [12] models fundamental limits in positional accuracy by gradient sensing. However, at the same time, the bacterium is changing position and orientation at some rate. If the bacterium spends more time to measure concentration, the bacterium may have drifted into a new orientation, and the concentration measurement will correlate less with the current orientation. In the case of a carrier which can adhere to a surface, the carrier may be able to spend more time to measure concentration while maintaining orientation.

D. Combining beacon measurements

In the case of bacterial chemotaxis, bacteria perform a simple comparison of local concentration to determine if a new position is closer or further from a location with beneficial molecules. In the proposed system it is necessary to combine several beacon measurements for the carrier to decide whether it is moving towards the receiver. In beacon routing from wireless networks [8], the wireless device calculates the position according to distances to the beacons and selects the beacon closest to the desired location. However, in the proposed system, a carrier is a nanomachine with limited computation ability. Thus, a carrier may not be able to calculate its three dimensional location and distance to the receiver. Also, the beacon routing in wireless networks has local minima (i.e. not at the destination, but all adjacent devices are further than the current device), and thus a greedy routing may fail without a backtracking method.

In this paper, for simplicity, the carrier approximates its distance by summing up the distance from each from the beacons. Assume the carrier is at position $P = (p_1, \ldots, p_n)$ then the approximated distance from the carrier to the receiver is

$$\sum_{1}^{i=n} \left| p_i - d_i \right|. \quad (1)$$

In the proposed system, addition is expected to be a simple molecular operation to combine multiple distance measurements. However, if a carrier has concentration of a type of molecule at a location and not the actual distance, then additional error may be introduced in identifying coordinates of a carrier. Also, estimating distances by addition of beacon distances can produce multiple local minima. A local minimum is a point at which all adjacent points are measured as further away from the receiver. For example with 3 beacons, additional local minima may occur at locations which have two correct beacon distances and one incorrect beacon distance. Local minima without the receiver may be avoided in the system by noisy movement of the carrier which can propagate out of a local minimum.

E. System Evaluation

The proposed system is applied to transmitting information in a carrier to a receiver at a location. The ideal carrier propagates to the receiver reliably and with low delay. Reliability is measured by the success rate: the probability of a carrier arriving at the receiver within a given time interval. Reliability is affected by noise in carrier measurement of distances and carrier propagation. Delay is the time necessary for the carrier to propagate from a transmitter to the receiver. The distribution of propagation delays is expected to have significant variance since carrier tumbles randomly orient a carrier and the environment produces random noise in carrier position over time.

Another important criterion in the proposed system is the accuracy with which a carrier detects location. A carrier detects location by distance measurements; however, distance measurements have limited accuracy (i.e. accuracy reduced by environmental noise and carrier movement). Thus, if two receivers are too close to each other, then a transmitter cannot guarantee exclusive transmission to only receiver and no other receiver. However, since the specific carrier chemical processes are not considered in this paper, accuracy of location detection is not discussed further.

III. NUMERICAL RESULTS

This paper evaluates the proposed system through simulation modeling. In the simulation model, a beacon produces a fixed concentration gradient and the carrier is a bacterium performing chemotaxis. Bacterial chemotaxis was chosen since it is a working system in nature and a large amount of existing work has produced detailed models of bacterial chemotaxis. This paper describes Monte Carlo simulation of the model and evaluates the system in terms of success rate and delay.

A. Simulation Model

The simulation environment is an infinite 2-dimensional space. Beacons are simplified as single points in space which produce a concentration gradient of molecules (e.g. the beacon is an enzyme and reacts with molecules supplied by the

environment at a constant concentration). For simplicity, the concentration gradient is assumed to be at the steady state.

A carrier is modeled as a 1 μm diameter bacterium capable of chemotaxis. The bacterium approximates the movement of bacteria observed in nature and follows the modeling described in [5], which includes rotational drift during bacterium runs and biased tumbling to a certain distribution of angles. In nature, a bacterium measures a noisy molecule concentration to measure distance; however, this paper focuses only on the impact of bacteria movement on propagation and assumes that the carrier measures the exact distance to beacons. Thus, there is no loss of distance measurement accuracy from concentration detection or translation of a concentration into a distance. The carrier approximates distance measurement by adding the distances to each beacon as described in Eq. (1). The model in this paper simplifies the expected run lengths as 1.25 seconds in the case of the distance measurement increasing (i.e. likely to be moving away from the receiver) and 10.0 seconds in the case of the distance measurement decreasing (i.e. likely to be moving towards the receiver).

The receiver is modeled as a 1 μm sphere in space. A transmitter communicates to the receiver successfully when the carrier containing information of the transmitter comes into contact with the receiver. Each transmitter is assumed to be uniformly anywhere within the area of the 1000 μm circle surrounding a receiver and transmits a single carrier. For each simulation, data points are of 10,000 independent transmitters transmitting to 1 of 10 receivers. Simulation code was built on top of the MASON multi-agent simulator [13]. Molecules and transmitters are assumed to not interfere with each other.

B. Number of Beacons

A molecular communication system can use various numbers of beacons to produce a coordinate system. This paper considers the case of 0, 1, 2, or 3 beacons positioned in a 2-dimensional space. Increasing the number of beacons (for 0, 1, 2, or 3 beacons) is likely to increase the success rate of a carrier reaching the receiver.

- With |B|=0 (i.e. coordinate system with no beacons), the carrier carriers undergo a random walk.
- With |B|=1 (i.e. coordinate system with 1 beacon), the carrier moves towards a circle of radius d_1 (i.e. the receiver is at distance d_1 from the beacon) and spends time to randomly search throughout the circle for the receiver. In the case |B|=1, the beacon is placed at the center of the coordinate space. Fig. 3 illustrates the circle representing the coordinate d_1. When |B|=1, all points on the circle have the same coordinate and a carrier cannot distinguish where on the circle the receiver is until the carrier randomly contacts the receiver.
- With |B|=2 (i.e. coordinate system with 2 beacons), a receiver has 2 coordinates (i.e. (d_1, d_2)). However, there are two points in the beacon coordinate space with the coordinates (unless the receiver is on the line passing through B_1 and B_2) (see Fig. 4). Thus with |B|=2, a carrier may propagate to the point which does not have the receiver. However, because of the noisy propagation of the carrier, the carrier may still propagate between the two points and thus contact the receiver. In the simulation of $|B| \geq 2$, the beacons are placed evenly about a circle with a diameter of 1000 μm. 1000 μm was chosen as it is a range within which a bacterium can measure distances using a single type of molecule [5].
- With |B|=3 (i.e. coordinate system with 3 beacons), a receiver has 3 coordinates (i.e. (d_1, d_2, d_3)) which uniquely identifies the receiver location. However, the bacterium may still propagate away from the receiver. The carrier combines distance measurements using Eq. (1) and compares nearby locations to identify the direction to the receiver. If there are multiple local minima, some bacteria must propagate towards a worse strength value before it can arrive at the receiver. Thus, the location is an additional local minimum which attracts the bacterium, but does not lead the bacterium to the receiver. For example, in Fig. 5, local minima may occur at locations which are the intersection of only two beacons.

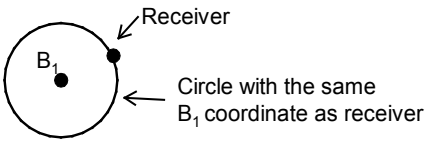

Figure 3. Location ambiguity in the case of 1 beacon. A circle represents the desired distance from the beacon at the center of the circle.

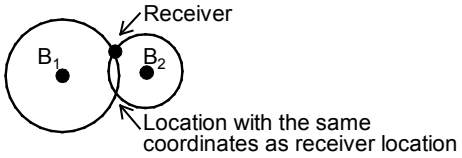

Figure 4. Location ambiguity in the case of 2 beacons. A circle represents the desired distance from the beacon at the respective center of the circle.

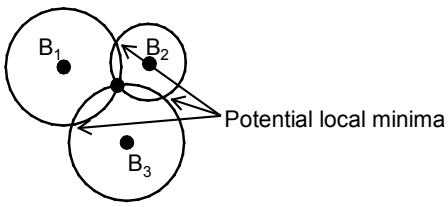

Figure 5. With 3 beacons, potential local minima occur at the intersection of two circles. The receiver is at the intersection of the three circles.

Fig. 6 illustrates the impact of the number of beacons (0, 1, 2, or 3 beacons) on success rate in reaching a receiver. Receivers were positioned at 1000 μm from the center of the coordinate system. For all numbers of beacons (i.e. 0, 1, 2, or 3 beacons), waiting longer increases the probability of the carrier reaching the receiver. In Fig. 6, there is a very wide variance in when the carrier contacts the receiver. For example with |B|=3, a carrier may arrive in the range of several minutes to a couple hours. Note that transmitters are not all at the same distance

from the receiver, therefore the illustrated variance is not the same as the variance in arrival time of a single carrier.

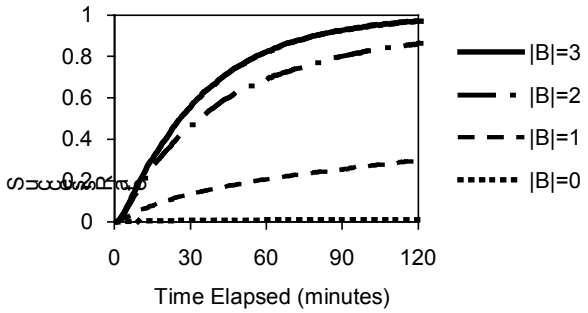

Figure 6. Success rate versus time for 0, 1, 2, or 3 beacons

Increasing the number of beacons significantly increases the probability of a carrier arriving at the receiver. As described above, as the number of beacons increases, the carrier propagates within a smaller area, and the carrier is more likely to encounter the receiver within a time interval if the area is smaller. This significantly reduces the time necessary for the carrier to encounter the receiver.

Fig. 7 illustrates the delay for 0, 1, 2, or 3 beacons for receivers positioned at 1000 µm from the center of the coordinate system. Similar to Fig. 6, delays have wide variance. As expected, delay decreases as |B| increases from 1 to 3 since the search space is decreasing. |B|=0 is not comparable since the success rate is significantly lower. In the case of |B|=0, a few molecules starting nearby the receiver are initially received, and other molecules are unlikely to contact the receiver.

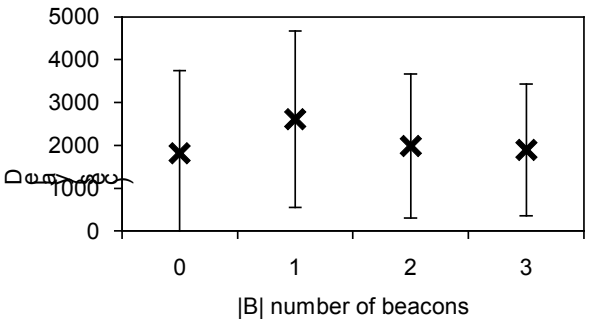

Figure 7. Delay for 0, 1, 2, or 3 beacons.

C. *Location of receiver*

The location of the receiver in the beacon coordinate system may impact the performance of the proposed system. The location of the receiver influences the strength detected by the carrier at each location in space. The location of the receiver also determines the size and location of local minima. To evaluate the impact of location, receivers were placed randomly at various distances, *x*, from the center of the circle on which the beacons are placed.

Fig. 8 illustrates the impact of distance *x* on propagation delay. Carriers propagate for 2 hours in each simulation.

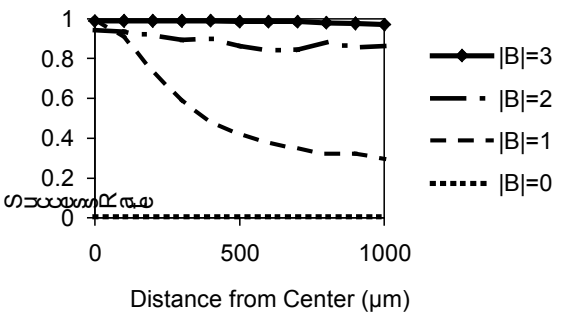

Figure 8. Success rate versus distance of the receiver from the center of the coordinate system for 0, 1, 2, or 3 beacons.

- In the case of |B|=0 (i.e. 0 beacon coordinate system), the success rate is independent *x*. Since transmitters are placed in the area of a circle around the receiver, the expected distance from transmitters to the receiver is independent of the placement of the receiver in the coordinate system.
- In the case of |B|=1, success rate decreases with distance. As distance increases, the radius of the circle illustrated in Fig. 3 increases. As the circle becomes larger, a carrier has a larger circle to search. The probability of contacting the receiver within a time interval becomes lowers as the search space increases, and the carrier becomes less likely to contact the receiver within 2 hours.
- In the case of |B|=2, success rate initially decreases with distance. In |B|=2, there are two local minima which have the same coordinates, and thus a bacterium may propagate to a local minimum without the receiver. As *x* increases, the local minima are likely to become further apart and there is lower probability for a bacterium to move from one local minimum to the other. However, as the distance becomes further in the case of |B|=2, the success rate begins to increase again. This occurs as an artifact of transmitter placement since transmitters are placed in a 1000 µm circle around the receiver. As the distance between local minima becomes greater and closer to 1000 µm, transmitters are more likely to start in the local minimum which contains the receiver.
- In the case of |B|=3, success rate appears independent of *x*. There are potentially four local minima. Bacteria are more likely to stay in the local minimum containing the receiver, which is the largest of the local minima. Similar to the case of |B|=2, |B|=3 is likely to also have an artifact of transmitters starting in the local minimum of the receiver as *x* becomes larger.

The randomness in bacteria movement is sufficient to overcome local minima. In the case of |B|=2, if the bacteria cannot propagate out of local minima, then at most half of the bacteria will be received, and the other half will be at the other local minimum without the receiver. Fig. 8 shows that |B|=2 achieves greater than 0.5 success rate, and thus bacteria with some probability can overcome problems of multiple local minima. Since there is a constant, non-zero probability that a

bacterium contacts the receiver within a time interval, all bacterium should eventually be received. The case of |B|=3 similarly supports the conclusion that bacteria overcome local minima. Almost all bacterium with |B|=3 arrive at the receiver, whereas a lower success rate would be expected if local minima trapped bacterium.

Fig. 9 illustrates the impact of distance *x* on delay. Variance in delay (not illustrated in Fig. 9) is relatively large for all distances and is consistent with Fig. 7. In the case of |B|=0, delay is independent of distance. In the case of |B|=1, delay is expected to increase with distance from the center of the coordinate system, since bacteria perform a random search in a circle with circumference proportional to *x*. At distances greater than 200 μm, success rate for |B|=1 is decreasing, and delays are not comparable (delays are only measured for successful transmissions). In the case of |B|=2 as described above, there are several factors (i.e. factors of increasing distance and simulation artifacts) impacting the success rate which are also likely to have similar impact on delays. Delay for |B|=3 is relatively independent of distance from the center of the coordinate system. Since delay is relatively independent of distance, time necessary to propagate the receiver is likely dominated by the time necessary to contact the receiver. For example, although the bacterium is close to the receiver, the bacterium may not be oriented to contact the receiver. As a result, the bacterium passes by the receiver, begins to propagate away from the receiver, and must tumble again before it has another chance to contact the receiver.

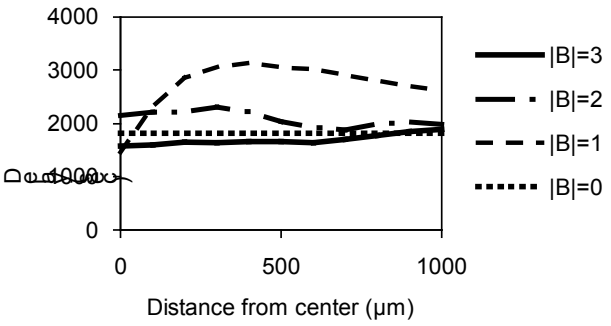

Figure 9. Delay versus distance of the receiver from the center of the coordinate system for 0, 1, 2, or 3 beacons.

IV. CONCLUSIONS

This paper described a molecular communication system in which a transmitter transmits molecules to a location in a relative coordinate system. A location in the relative coordinate system is determined by measuring distances through molecular communication to one or more beacons. The proposed system can potentially be used to address receivers by location. Addressing by location can provide new functionality to molecular communication systems and introduce new applications for molecular communication.

The proposed molecular communication system was evaluated through Monte Carlo simulation and was found to increase success rate and reduce the delay in locating a receiver identified with beacon coordinates. Future work includes detailed design of carriers and evaluation of the granularity of addressing resolution in the coordinate system.

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