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GEOGRAPHIC GREEDY TRIPLEWISE GOSSIP ALGORITHM FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

A novel gossip algorithm for distributed averaging with fast convergence and reduced cost of communication over wireless sensor networks (WSNs) is proposed in this paper. This algorithm is proved to improve the behaviour of the standard gossip algorithm (SGA), triplewise gossip algorithms (TGAs) and the geographic gossip algorithm (GGA) by exploiting the geographic information of the network. An analysis of convergence time and cost of communication of the proposed algorithm is performed and a comparison with other existing methods is provided.

KEYWORDS

Wireless Sensor Networks, Distributed Computing, Distributed Processing, Gossip Algorithms, Routing.

1. INTRODUCTION

Agreement/consensus of sensed information is one of issues of distributed signal processing in WSNs. Averaging the initial value of all the nodes in the network is an example of aggregate problem. Distributed averaging methods are widely used to solve agreement problems [1]. Gossip algorithms are widely used in distributed signal processing. Centralized computing, on the other hand, involves collecting data from all network nodes. In centralized computing, computations are performed at a fusion center. Distributed networks consume more power than their centralized counterparts do; the energy consumption depends on the number of radio transmissions and the total number of iterations until convergence. Distributed averaging algorithms have to be designed to avoid unnecessary waste of power and time. Among the advantages gained, gossip algorithms are robust against link failures and a communication bottleneck near the fusion center is avoided [2]. Sums and averages constitute building blocks for many signal processing applications, such as Gram-Schmidt orthogonalization [2]-[3], WSN node localization [4] and linear parameter estimation [5], to name just a few. Gossiping is a modified version of flooding, where the nodes do not broadcast a packet, but send it to a fully or not fully randomly selected neighbour/s. Gossiping avoids the problem of implosion of the network due to collision, but it takes a long time for message propagation throughout the network [1]. Though gossiping has considerably lower overhead than flooding, it does not guarantee that all nodes of the network will receive the message. It relies on the random neighbour selection to eventually propagate the message throughout the network. Gossip algorithms are employed to calculate the average of measurements of a WSN. In a typical pairwise gossip algorithm such as SGA [6]-[7], one node i wakes up at each iteration with probability $P=1/N$, where N is the number of sensor nodes, and performs averaging with one of its neighbors j at random with probability P_{ij}; iterations continue with slow convergence [1], [5]-[8]. SGA has another disadvantage in that it wastes a lot of energy among all gossip algorithms because of significant recalculation of redundant information. This result motivated Dimakis *et* *al.* [8] to modify the SGA by averaging with far away nodes resulting in the introduction of the so-called GGA. The latter algorithm accelerates the averaging process by averaging between any pairwise nodes in the whole network, exploiting the geographic information of activated nodes and their neighbors [1], [5], [8]-[9]. Triplewise gossip algorithms (TGAs), e.g. standard TGA and greedy TGA (G-TGA) accelerate the pair wise averaging methods (GGA and SGA) even further by averaging between three nodes per iteration instead of between only two nodes [10]. In standard TGA, at each iteration, one node wakes up and performs averaging with two of its neighbors at random. G-TGA has been proposed to reduce the time of convergence allowing the activated node to choose two neighbors with different measurements (minimum and maximum) [10]. Averaging/summing aggregate problems show up in distributed sensor networks, while averaging/summing agreement problems do not arise in centralized sensor networks [1]. Distributed consensus algorithms are not confined to WSNs, and they can be applied to distributed processor computing [11], distributed data base management or distributed signal processing on the Internet for example [1]. In distributed manner, every node has a local information. In a cluster-based WSN, it is still not possible to apply gossip algorithms on it. Each cluster needs a fusion centre to connect to the gate way. The fusion centre requires entire information about the cluster, while aggregate values do not need entire information. The latter point makes gossiping more robust against link failure and not possible to apply on cluster-based WSNs.

The proposed algorithm, named geographic greedy triplewise gossip algorithm (GGTGA), exploits the good points in both G-TGA and GGA to improve both convergence time and cost. The rest of the paper is organized as follows. The problem formulation including distributed averaging, network model and time model is presented in Section 2, then our algorithm (GGTGA) is proposed and analyzed in Section 3. Simulation results and conclusion are presented in Sections 4 and 5, respectively.

2. PROBLEM FORMULATION

2.1 Distributed Averaging

In WSN with N nodes, the i^{th} node has an initial scalar measurement, $x_i\,(0)$, in some modality of interest (e.g., temperature, pressure, light, …etc.). The aim of the averaging algorithms is reaching the global average $x_{ave} = \frac{1}{N}\sum_{i=1}^{N} x_i(0)$ from the local measurements [1], [5]-[8] and [10]. We are interested in the number of iterations or rounds required for convergence and the number of radio transmissions passing through the network during the averaging process. At each round $t = 1{:}T_{ave}$, a set of nodes updates their estimations [1], [5]-[10], where T_{ave} represents the total practical time of convergence of true global averaging. The gossip algorithms converge to the almost surely true average if $P\left[\lim_{t\to\infty} \varepsilon(t) = 0\right] = 1$, where $\varepsilon(t) = ||\boldsymbol{X}(t) - x_{ave}\mathbf{1}||_2$ is the estimation error, $\boldsymbol{X}$(t) is the $N*1$ vector of measurements, and **1** is the $N*1$ unit vector [12]-[13]. The gossip algorithms operate as follows: At each round in a set of nodes, at least two nodes are averaging and updating their estimations per round. Let $S(t)$ represent a set of nodes at time t and $x_i(t)$ the estimation value for $node\ i \in S(t)$. The nodes update their estimations according to Equation (1):

$$x_i(t) = \frac{1}{|S(t)|} * \sum_{i\in S(t)} x_i\,(t-1)\ . \tag{1}$$

The rest of the nodes remain unchanged in this round [11]:

$$x_k(t) = x_k(t-1)\ . \tag{2}$$

Table 1. Key term's definition.

Item	**Definition**
Time of convergence:	The time of convergence is the total time accounted until $\boldsymbol{X}(t) = x_{ave}\,\mathbf{1}$ is reached.
Communication cost:	The number of the entire messages spent until reaching the exact convergence.

2.2 Network Model

Sensor nodes deployment strategies play an important part in the performance of networks. Many topologies can be found in the wireless model such as ring, grid and random geometric graph (RGG) …etc. The random geometric graph G (*N*,*r*) is an irregular model and suitable topology for WSN. RGG is formulated by choosing *N* nodes uniformly and independently in the unit square $[0,1]^2$, [1], [5], [8] and [10]. The transmission range of a node is $r = \sqrt{\frac{c * \log(N)}{N}}$ in order to maintain connectivity and prevent interference [10]. The radio transmission range *r* plays an important role in convergence; small radio transmission ranges result in slow convergence, even for fast averaging algorithms [6]. Therefore, *r* must be set carefully. The constant *c* will be assigned the value $c=2$, which is the suitable value for the TGA algorithms [10] in order to test all the considered algorithms under the same conditions to compare their behavior.

2.3 Time Model

We use an asynchronous time model, which is a more suitable time model for distributed networks. In the asynchronous time model, each node has an independent clock, which ticks at the random time rate λ following a Poisson process. The inter-tick times between each two iterations are independently and identically distributed (i.i.d) and are inversely proportional to $N\lambda$. If λ is small enough, then there is only one iteration at a time with high probability and each communication has greater chance to succeed. If λ is too large, then there is a high chance that a node becomes activated while another node is still operating. In this case, and if the network has a huge number of nodes, the network nodes are prone to failure in updating their estimates [1], [6]-[13].

2.4 Gossip Algorithms

2.4.1 Pairwise or Standard Gossip Algorithm (SGA)

This is also called nearest-neighbour gossip algorithm, the earliest distributed averaging method proposed by [5]-[6]. At each round, the asynchronous averaging algorithm activates one node (*s*) at random and averages its value with one–hop neighbours (*d*) at random with probability P_{sd}. Both sensor nodes update their values by replacing their own value with the calculated average. The averaging is done by putting 0.5 in indices (*s*,*s*), (*s*,*d*), (*d*,*s*) and (*d*,*d*) of the identity matrix W(t), where W(t) is a random, symmetric, doubly stochastic, independent and identity matrix [13]. Algorithm 1 explains the pairwise gossip strategy systematically.

Practically, time convergence can be defined as the first time when $\|\boldsymbol{X}(t) - x_{ave}\mathbf{1}\|_2$ equals zero [9]. This algorithm converges slowly and wastes energy because of significant recalculation of redundant information. This motivated other researchers to propose other distributed averaging methods. Communication cost can be theoretically and practically calculated. Practically, SGA costs two message transmissions per round and therefore the total number of messages is calculated as:

$$Cost\ (practical)\ =\ total\ time\ practically\ calculated * 2\quad . \tag{3}$$

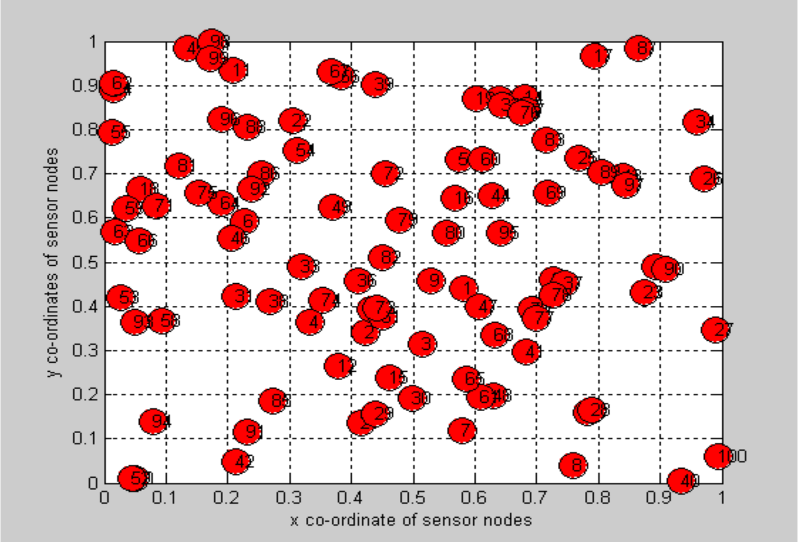

Figure 1. Sensor Nodes Distributed in RGG.

Theoretically, the cost of SGA is computed by $cost = o(\frac{N}{r^2}\log(\epsilon^{-1}))$ for $r = \sqrt{2 * \log(N)/N}$. he equation for the cost becomes [8]:

$$Cost\ (theoretical) = O(\frac{N^2}{2*\log(N)}\log(\epsilon^{-1})), \tag{4}$$

where value of ϵ represents averaging accuracy between (0,1).

Algorithm 1: Standard Gossip Algorithm:

```
1. for t=1: $T_{ave}$.
2. s=activated node at random.
3. d=neighbor node to node (s) selected at random.
4. $x_d(t) = \frac{x_d(t-1)+x_s(t-1)}{2}$, the new estimate is sent back to node(s).
5. $x_s(t) = x_d(t)$.
6. end for.
```

2.4.2 Geographic Gossip Algorithm (GGA)

This algorithm was proposed after a disappointing result of slow mixing time of SGA and waste of energy due to significant recalculation of redundant information. GGA is an asynchronous algorithm that accelerates the pairwise standard averaging by exploiting geographic information of nodes as well as geographic location of their neighbours. Thereby, GGA is able to route a node's estimation value to far away nodes in RGG, by utilizing greedy routing towards the destination [8], [14].

At each round, one node is activated, a location point (*xd*,*yd*) is chosen and greedy route towards the closest node to the chosen location is started. The receiving node calculates pairwise average and utilizes the route in reverse. The activated node will receive the new estimate and update its value. Algorithm 2 shows the behaviour of GGA. Routing is expensive in terms of communication cost. Nevertheless, it is the reason for achieving convergence acceleration by gossiping with random nodes, which are far away in the network [8]. GGA saves a factor $\sqrt{\frac{N}{log\ N}}$ over SGA in terms of communication cost on RGG so the equation will be as follows [8]:

$$Cost\ (theoretical) = O(\frac{N^{1.5} * \log\ \epsilon^{-1}}{2 * \sqrt{\log(N)}}). \tag{5}$$

The number of messages is not constant at each round, thus the number of messages cannot be calculated practically, since the route is variable in length at each round. In terms of time of convergence, the estimation error equation is used to show the practical time for convergence. The time required for convergence can be computed theoretically depending on Equation (6) in terms of ϵ [8]:

$$T_{ave}(theoretical) = O(N * \log \epsilon^{-1}). \tag{6}$$

Algorithm 2: Geographic Gossip Algorithm:

```
1. for t=1: $T_{ave}$.
2. s=activated node at random.
3. (xd,yd) selected point by node (s) starts greedy routing toward the closest node to the chosen point.
4. d =is the closest node.
5. $x_d(t) = \frac{x_d(t-1)+x_s(t-1)}{2}$, the new estimate is sent back to node (s) through the same route.
6. $x_s(t) = x_d(t)$.
7. end for.
```

2.4.3 Standard Triplewise Gossip Algorithm (Standard TGA)

TGA is a recently introduced, asynchronous algorithm that enhances the distributed ability by enlarging the gossip group and thereby reaching a good estimation of the average with fewer rounds and less communication cost [10]. In SGA, the communication complexity is very high on RGG [1], [7].

In standard TGA, at each round, one node wakes up at random, selects two of its neighbours at random and averages their estimations and then all these three nodes update their values to be equal to the new local averaging estimation. There is an exception when the number of neighbours for the activated node is equal to one, then pairwise averaging is performed instead of triplewise averaging [10].

Practically, standard TGA costs four message transmissions per round. One transmission is required from the source node (s) to two destination nodes (d_1 & d_2) and two transmissions from (d_1 & d_2) to (s). Finally, node (s) calculates the averaging of three nodes (s, d_1 & d_2) and transmits the new estimation to both nodes (d_1 & d_2) [10]. Algorithm 3 illustrates the averaging method by standard TGA.

$$Cost\ (practical) = total\ practical\ time\ required\ for\ convergence * 4. \tag{7}$$

Algorithm 3: Standard Triplewise Gossip Algorithm:

```
1. for t=1: $T_{ave}$.
2. s=activated node at random.
3. node (s) sends a broadcast message to all its neighbors.
4. $d_1$ & $d_2$ =two neighbor node to node (s) which was selected at random.
5. $x_s(t) = \frac{x_{d1}(t-1)+x_s(t-1)+x_{d2}(t-1)}{3}$, the new estimate is sent back to nodes ($d_1$ and $d_2$).
6. $x_{d1}(t) = x_{d2}(t) = x_s(t)$.
```

```
end for.
```

2.4.4 Greedy–Triplewise Gossip Algorithm (G-TGA)

This is an asynchronous algorithm almost identical to standard TGA, but instead of the activated node dealing with two neighbours at random, G-TGA deals with two neighbours having specific different values. This point improves the time for convergence more than standard TGA and then provides less message transmissions. The activated node chooses two of its neighbours: one having the minimum estimate and the second having the maximum estimate among all neighbours. This algorithm requires six message transmissions per round. Algorithm 4 explains the behaviour of G-TGA systematically. Node (s) is activated, then two neighbour nodes N_s are selected one with the maximum value and the second with the minimum value among all neighbours of the activated node. First, 4-radio transmission is required as in standard TGA; after the activated node changes its value, the two destination nodes will update and broadcast their values [10].

$$Cost\ (practical) = total\ practical\ time\ required\ to\ convergence * 6. \qquad (8)$$

Algorithm 4: Greedy-Triplewise Gossip Algorithm:

```
for t=1: $T_{ave}$
    s=activated node at random
    node (s) sends a broadcast message to all its neighbors
    $d_1$ & $d_2$ =two neighbors of node (s) and having different values
    $d_1$ =node has a minimum value
    $d_2$ =node has a maximum value
    $x_s(t) = \frac{x_{d1}(t-1)+x_s(t-1)+x_{d2}(t-1)}{3}$ The new estimate is sent back to nodes ($d_1$ and $d_2$)
    $x_{d1}(t) = x_{d2}(t) = x_s(t)$
end for.
```

3. GEOGRAPHIC GREEDY TRIPLEWISE GOSSIP ALGORITHM (GGTGA)

Our algorithm is proposed to reduce the number of radio transmissions and of iterations to reach global convergence. Every node has known its location and the geographic location of its neighbours. For each $t=1, 2, \ldots, T_{ave}$, one node is activated and chooses a location point (x_d,y_d) at random. The activated node will use greedy routing toward two nodes within the transmission range of the chosen location, one of them having the minimum value measurement and the other having the maximum value among the other nodes in the transmission range. The activated node (s) will send its activation message to the two chosen nodes (d_1 & d_2) by forwarding the message through the path.

The two destination nodes (d_1 & d_2) will receive the activation message of node (s), then the destination nodes will send their estimated values (the maximum and minimum estimation values) to node (s) using the same route that node (s) followed to send its activation message to (d_1 & d_2). The activated node (s) will compute the average of its value and the values of the two destination nodes according to the following equation:

$$x_s(t) = \frac{x_s(t-1)+x_{d_1}(t-1)+x_{d_2}(t-1)}{3} \qquad (9)$$

Then, node (s) uses the same route to forward the new updated value to both nodes (d_1 & d_2). At the end of the iteration, Equation (10) results, while the remaining nodes remain unchanged as in Equation (11):

$$x_{d_1}(t) = x_{d_2}(t) = x_s(t), \tag{10}$$

$$x_k(t) = \quad x_k(t-1)\,. \tag{11}$$

If we let $\boldsymbol{X}$(t) indicate the vector of estimated values at the end of the time slot *t*, then the algorithm execution can be described as a sequence of iterations:

$$\boldsymbol{X}(t) = \boldsymbol{W}(t)\boldsymbol{X}(t-1), \tag{12}$$

where **W** is the weighted averaging matrix [10]. **W** is a random, symmetric, doubly stochastic and semi definite-programming selected averaging matrix. **W** (t) is an i.i.d selected matrix at every time round [1], [5], [9]-[10] and [14]. For any gossip algorithm $\mathbf{W}^2$=**W** at each round, i.e., **W**(t) is a projection matrix since averaging the same set twice no longer changes the vector **X**(t) [1], [4].

Let $\alpha_{i,j} = e_i - e_j$, where $e_i = [0,0 \ldots.,1,\ldots,0]^T$is an *N*1* unit vector with i^{th} element equals 1. With probability $\frac{1}{N} * P_{i,j} * P_{i,k}$, the random symmetric matrix $\boldsymbol{W}(t)$ is:

$$\boldsymbol{W}_{i,j,k} = I - \frac{\alpha_{i,j}{\alpha_{i,j}}^T + \alpha_{i,k}{\alpha_{i,k}}^T + \alpha_{j,k}{\alpha_{j,k}}^T}{3}. \tag{13}$$

Algorithm 5: Geographic Greedy-Triplewise Gossip Algorithm (GGTGA):

```
for t=1: $T_{ave}$.
    s=activated node at random.
    (xd,yd) selected point at random by node (s) starts greedy routing toward the two nodes within transmission range of the chosen point, one with the maximum value and the other with the minimum value.
    d1 =node with the minimum value sends its value to node (s).
    d2 =node with the maximum value sends its value to node (s).
    $x_s(t) = \frac{x_{d1}(t-1)+x_s(t-1)+x_{d2}(t-1)}{3}$, the new estimate is sent back to nodes (d1 and d2).
    $x_{d1}(t) = x_{d2}(t) = x_s(t)$.
end for.
```

Nodes require memory to save this information. Sensor nodes that need to save nodes location call for additional memory requirements. This is the weakness point of our proposed algorithm GGTGA and GGA.

3.1 Time of Convergence

The convergence time of the proposed algorithm will improve over that of G-TGA, standard TGA, GGA and SGA, as we will show in Section 4 in the simulation results. For GGA, the convergence time T_{ave} is theoretically given by Equation (6), where ϵ is the averaging accuracy with values between 0 and 1 [8]. The value of ϵ is very important for the calculation of the communication overhead for GGA in Sub-section 3.2 below, since the number of messages per round is not constant. It gives the level of accuracy and takes the same value that was taken in Equation (6). Practically, all gossip algorithms depend on the estimation error function to see the speed up of distributed averaging algorithm. Many methods can be used to accelerate convergence, such as adding a shift register [15], but additional hardware causes the node to consume power and increases its size. Other algorithms use the broadcast property for communication, such as broadcast gossip algorithm (BGA) [16]. BGA has a lot of disadvantages; it needs to optimize certain parametric values well like (γ) [16] and does not converge to the correct average of initial value of all nodes [10]. Deterministic averaging algorithms are faster than randomized averaging algorithms (gossip algorithms), putting conditions for the selection of destination nodes which helps accelerate convergence, while full randomization increases redundancy and hence slows convergence. If the selection of nodes is not fully random, the convergence time will be enhanced.

3.2 Communication Cost

Now, we need to see how our algorithm reduces the number of radio transmissions as well. It is worth noting that the number of messages in GGA and the proposed GGTGA is not constant per iteration, since it depends on the path it takes in each iteration. So if we find the average cost per iteration in GGA, we can estimate the communication cost for the proposed GGTGA by proportionally taking into account the convergence time T_{ave} obtained practically for GGTGA. The rationale behind this assumption is that GGTGA also employs geographical routing as in GGA, and therefore, the average communication cost in a path should be comparable. The result is then multiplied by 2 to account for the two routes of GGTGA. Although this communication cost would only be an estimate, it is at least guaranteed to be of the same order of magnitude of the exact value.

4. SIMULATION

We use Matlab to simulate and consider a static, time invariant [13] connected network consisting of 100 nodes that are uniformly and independently distributed in the unit square $[0,1]^2$. We will first consider the convergence times for G-TGA, GGA and SGA and compare them with that of the proposed GGTGA. Figure 2 shows the convergence time that results in an estimation error $\varepsilon(t) = ||\boldsymbol{X}(t) - x_{ave}\mathbf{1}||_2$ equal to zero [9], [13].

As is clear from Figure 2, GGTGA needs only 323 iterations. It remarkably accelerates the time for convergence. The slowest algorithm, which has a slow mixing time, is SGA. It needs 7213 iterations for convergence. The convergence times for the different algorithms are shown in Table 2. Figure 3 shows the logarithmic representation of the estimation error given by Equation (14) below [9], [13]:

$$\varepsilon(t) = log(||\boldsymbol{X}(t) - x_{ave}\mathbf{1}||_2). \tag{14}$$

We now turn to the calculation of the number of radio transmissions. Substituting the practical value of T_{ave} of Table 2 for GGA in Equation (6) that represents the theoretical convergence time for GGA, and assuming exact equality, we compute ϵ for GGA in order to substitute it in the corresponding equation to obtain the number of radio transmissions. As for the proposed GGTGA, the communication cost is found as outlined in Section 3.2.

Figure (4) and Figure (5) represent simulation for the number of message-passings for each presented gossip algorithm. Table 2 shows the number of radio transmissions for the various algorithms as well as the required ϵ if needed. GGA needs ϵ in order to get the expected number of messages, since the number of messages per round is not constant. With a level of accuracy equal to ($3.1623e^{-016}$), the expected cost is almost 4 messages per iteration for GGA and thus we can deduce the expected cost for our proposed algorithm GGTGA. We calculate the expected cost per iteration, since the greedy routing is found at each iteration. There is a trade-off between the level of accuracy and the number of both iterations and message-passings.

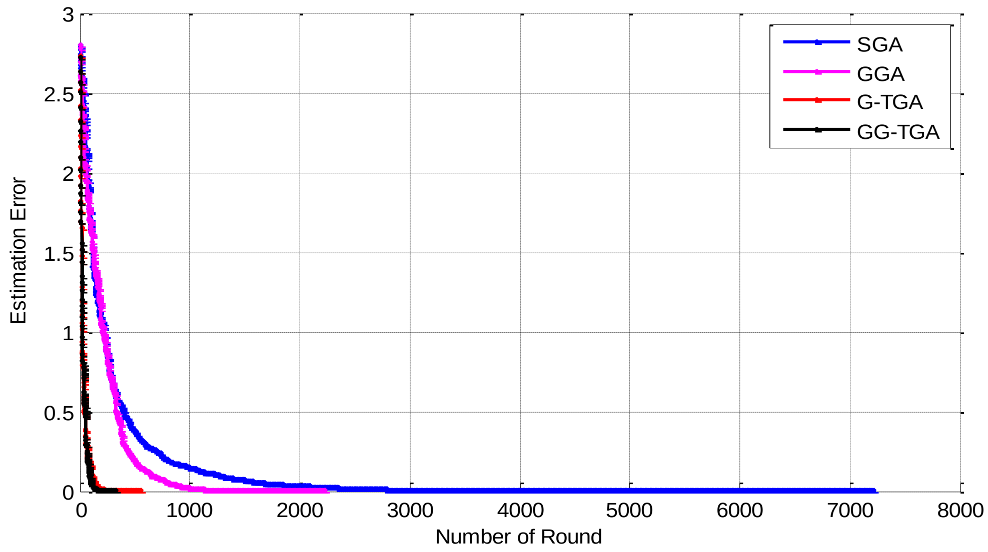

Figure 2. Convergence of Various Gossip Algorithms.

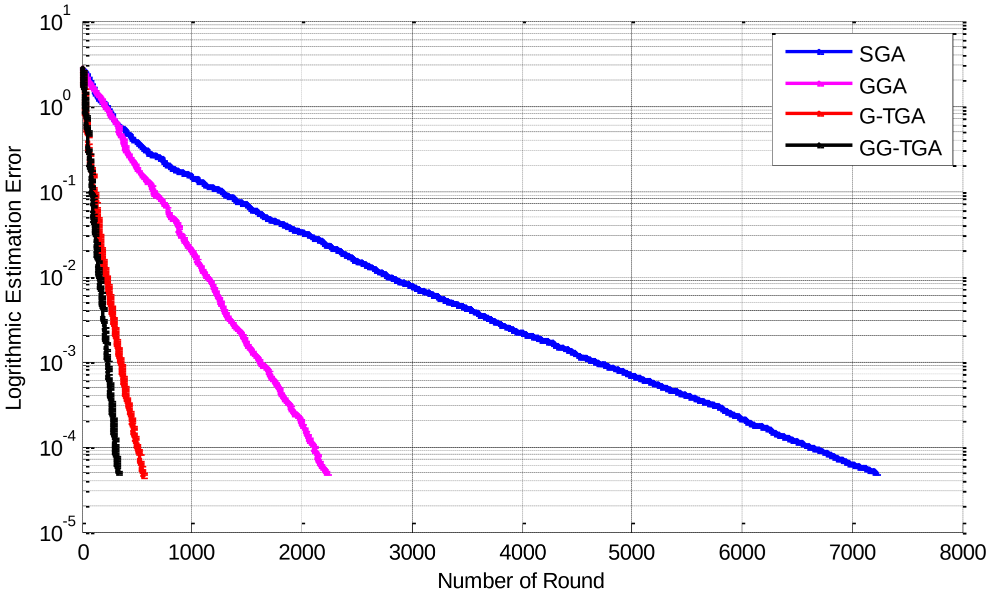

Figure 3. Logarithmic Convergence of Various Gossip Algorithms.

Table 2. The behaviour of different gossip algorithms.

Aggregate Algorithm				
Parameter evaluation	**SGA**	**GGA**	**G-TGA**	**GGTGA**
Number of iterations	7213	2224	552	323
ϵ	/	3.1623e^{-016}	/	/
Number of messages	14426	8896	3312	2584

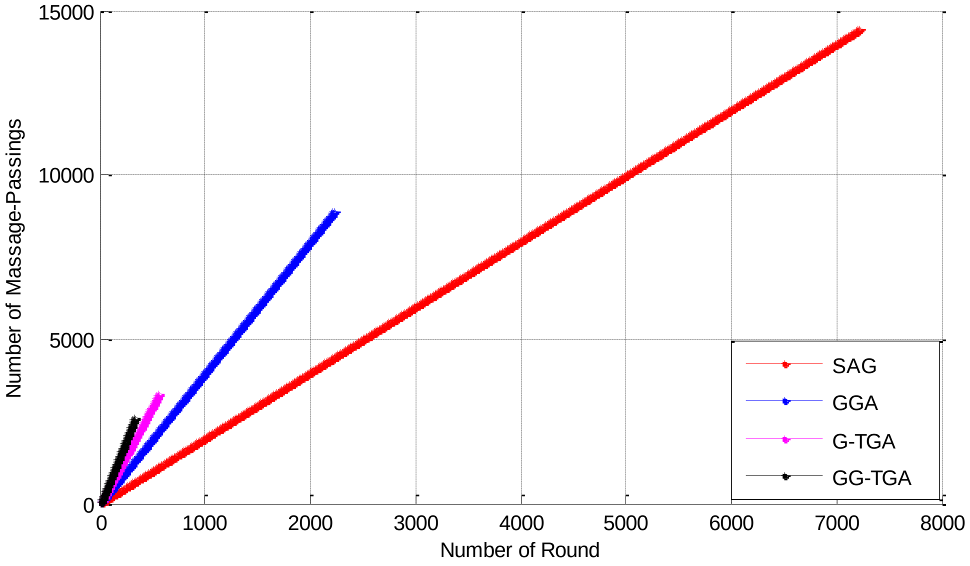

Figure 4. Linear Representation of Communication Overhead for Different Gossip Algorithms.

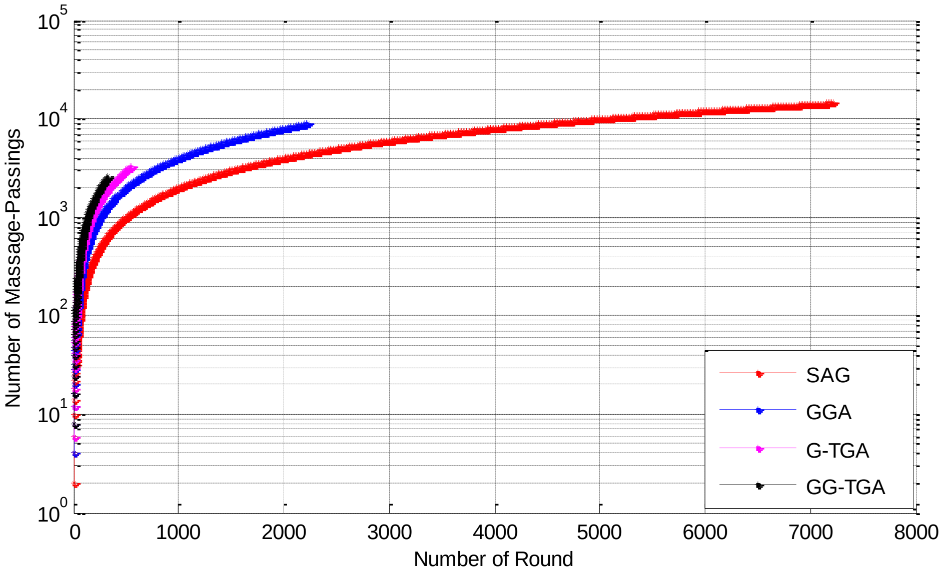

Figure 5. Logarithmic Representation of Communication Overhead for Different Gossip Algorithms.

5. CONCLUSION

Deterministic averaging algorithms are faster than randomized averaging algorithms (gossip algorithms). Putting conditions for the selection of destination nodes helps accelerate convergence, while full randomization increases redundancy and hence slows convergence. If the selection of nodes is not fully random, the convergence time will be enhanced with little cost. We propose a novel gossip algorithm that accelerates the time of convergence and reduces the number of radio transmissions needed to perform distributed averaging in WSNs. These two parameters determine the amount of power consumption in distributed WSNs. Our algorithm greatly reduced both convergence time and number of radio transmissions. Therefore, it was shown to outperform other existing gossip algorithms in terms of energy saving. Nodes require memory to save this information. Sensor nodes that need to save node locations call for additional memory requirements. This is the weakness point of our proposed algorithm GGTGA and GGA.

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ملخص البحث:

في هذه الورقة البحثية، يتم اقتراح خوارزمية غوسِب (Gossip) جديدة لإيجاد المعدّل الموزَّع وتمتاز بتقاربٍ سريع وكلفة منخفضة للاتصال مقارنةً بشبكات المجسّات اللاسلكية (WSNs).

وقد أثبتت الخوارزمية المقترحة تحسيناً للسلوك بالنسبة لخوارزمية غوسِب القياسية (SGA)، وخوارزمية غوسِب الثلاثية (TGA)، وخوارزمية غوسِب الجغرافية (GGA)؛ وذلك عن طريق الاستفادة من المعلومات الجغرافية للشبكة. وتقدم هذه الدراسة تحليلاً لزمن التقارب وكلفة الاتصال للخوارزمية المقترحة، إلى جانب مقارنة مع طرقٍ أخرى قائمة.