"Biologically Inspired Data Propagation and Aggregation Method for Wireless Sensor Networks"

J. Freeman[1], M. V. Ramesh[2], and A. Mohan[1]
[1]Dept. of Electrical and Electronics Eng., Amrita University, Amritapuri Campus, Kerala, India
[2]Dept. of Computer Science, Amrita University, Amritapuri Campus, Kerala, India

Abstract **-** *This paper presents a novel method of relaying data collected in a directed network towards a sink node. The data is dynamically correlated as the data messages propagate towards the sink node through the network. By simple mathematical means, the "strength" of the data can be increased or decreased based on it's correlation with other encountered data sets. In addition, the strengths of the messages are decayed or automatically reduced each time the data is propagated or relayed towards the sink node (unless it is boosted by correlation with other data). This sets up a dynamic between the strengths of messages being boosted by correlation and being reduced via decay. By letting irrelevant (low strength and uncorrelated) messages die, energy is conserved in the network through reduced message forwarding, congestion, and analysis. This is especially important in wireless sensor networks, where energy consumption should be minimized for maximum network lifetime and reliability.*
A mathematical model of how to achieve this scenario is presented here. Initial results are given.

Keywords: Wireless Sensor Networks, Biologically Inspired, Data Correlation, Message Propagation, Energy Conserving.

1 Introduction

Many different schemes exist for passing messages or data from one part of a network to another. Many of these involve some sort of multi-hop process. Aggregation algorithms may be distributed or they may be centralized [1]. Some argue that aggregation is a necessary core function of wireless sensor networks in order to reduce network traffic and conserve energy [2]. The idea behind this paper is to selectively filter out some of the less meaningful, irrelevant data, based on a very simple mathematical correlation method, before it reaches the sink node.

This work has come out of deliverables completed for the WINSOC[1] (Wireless Sensor Networks with Self Organizing Capability) project (www.winsoc.org), funded by the European Commission. This WINSOC project is composed of 11 academic, industry, and government partners in Europe and India. Amrita University is the deployment partner for implementing the wireless sensor network in landslide applications, among other duties. The prime aim of the project is to develop a new type of simple and inexpensive wireless sensor nodes that enable dense and widely deployed wireless sensor networks for environmental monitoring applications.

1.1 Biological inspiration

The biological inspiration of this algorithm can be derived from the example of the effects that pinpricks can have on someone's arm. There are a number of basic cases that arise, resulting from variations of the number and intensity of pinpricks. Initially, consider the case of weak and strong pinpricks in large and small quantities. Four distinct cases then arise.

1. A large number of strong pinpricks - the result is that one's attention will be strongly drawn to the arm. Thus the pinpricks convey very relevant information and the "network", the person's nervous system, relays this information on automatically.
2. A small number of strong pinpricks - the result is that one's attention will be attracted, but not as much as in case 1.
3. A large number of weak pinpricks - the result is again that the attention will be attracted a similar amount to case 2.
4. A small number of weak pinpricks - the person's attention will be drawn less than in all three cases above, and maybe even ignored completely.

There are three primary ideas that arise in this method that pertain to data aggregation and message propagation within sensor networks.

1. Statistically "strong" data should be given high importance and should reach the sink node.
2. A combination of either many weak data or few strong data should reach the sink node, but with less strength or statistical importance than case 1 immediately above.
3. Small amounts of insignificant data should be ignored.

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The key concept here is that correlation of messages with each other can increase their significance. In general, correlation is a factor that increases the significance of data. It would therefore be ideal if an aggregation scheme for a wireless sensor network included this factor. However, correlation by itself is not necessarily enough, as it can become unbounded and grow as the number of information generators increases. Therefore, a second biologically inspired idea is introduced, that of decay. In many systems, a greater distance between two objects implies that communication between the two objects in weaker. I.e. a message sent from a source is weaker the further it propagates from the source. In other words, it decays as it travels from its source. This is an essential property of message propagation in nature, as it is quite unnecessary that all information generated by a system be propagated indefinitely. For example, a bird can detect the strength of wind. It the wind becomes, very strong, as in a hurricane, the bird will seek shelter. But this is only the case when the bird is near to the hurricane. There is no need for the bird to seek shelter if the hurricane is very far away. Thus that information is not relevant.

Another simpler example is that of an elephant walking. Animals will feel the vibrations set up by an elephant's walk from a distance and know that an elephant is coming and they should make way before seeing it. However, if the vibrations of an elephant walking propagated indefinitely without decay, then another animal around the globe would be able to feel the walking of this elephant. Again, that is not relevant information. Therefore, decay is a way of establishing relevance. If a message has decayed beyond recognition, then a good case can be made for the fact that the information is not relevant to the current situation at hand.

A final example is that of a train crossing. A train coming to a crossing should obviously signal that it is approaching. But, this is only appropriate when the train is some certain distance from the railway crossing. If it signals to the railway crossing from a distance of 10 km that it is coming, and the gates are lowered, the result will be a lot of waiting by people trying to traverse the train crossing. In a similar manner, if the train notifies the crossing too late, then unwanted risks may occur or even worse. Therefore, decay is an essential property of natural propagation that limits the sphere of influence of information. In many cases, this is a beneficial aspect, rather than a negative component. There are exceptions to this, such as the modern telecommunication system, in which we ideally want infinite distance communication with no decay.

These two biologically inspired aspects of communication, correlation and decay, can be combined into one process that is suited well to wireless sensor networks. One aspect is that correlation can boost the strength or statistical significance of information as it propagates through a network. The other aspect is that decay degrades the strength of statistical significance of information as it propagates through a network. Thus these two "forces" oppose each other. These properties can be exploited to design a sensor network that follows these well established and natural scenarios.

2 Message propagation

Consider the directed network tree given in Figure 1 with two message sources, one at Node A and the other at Node B. Network message transmission is started at the lowest network level, i.e. at the node furthest away from the sink node and proceeds on a level by level basis toward the sink node. Assign a relevant strength of significance to the information that each node is transmitting into the network.

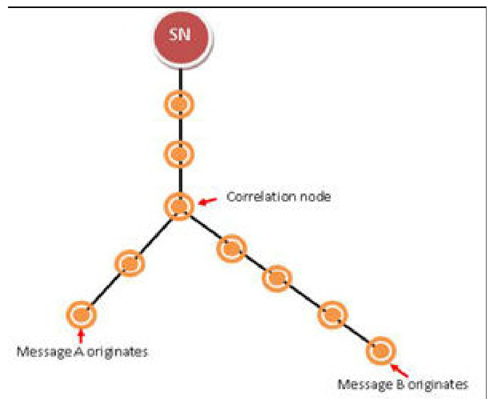

Figure 1 – Simple network structure

Let there be defined a rule of propagation such that for a message, *m*, each time the message is propagated or relayed towards the sink by another node, the message strength follows the function:

$$s_{n-1}(m) = s_n(m) - C_p \qquad (1)$$

where s is the strength or statistical significance of the message at the n^{th} node (Let n be defined as decreasing towards the sink node, with the sink node being zero), and let C_p be defined as the constant of propagation, or the amount by which the message is decayed each time it propagates.

Thus, after h number of message relay or propagation hops, the strength of a message will be given by

$$s_{n-h}(m) = s_n(m) - (h * C_p) \qquad (2)$$

For the message, *m*, originating at the lowest network level, which is h_m hops away from the sink node, and if the original statistical strength of the message is s_0(m), then the strength of the message at the sink node will be given by

$$s_0(m) = s_{hm}(m) - (h_m * C_p) \qquad (3)$$

Since the sink node is the center which will collect the relevant data and send it for analysis as in the landslide prediction or fire detection scenario for example, it would be ideal if the node originally broadcasting a message could determine the statistical strength of the information at the sink node itself. This is accomplished by determining the intended strength, I(*m*), of the message at the sink node.

The intended strength really represents a likelihood of the data reaching the sink node. This will have much broader applications in large networks operating under this scenario as it allows large amounts of potentially insignificant data to die off and stop propagating, thereby saving reception, processing, and transmission energy, while still allowing the significant data to reach the sink node for data analysis.

Using the above information and the propagation constant defined above, we can define the transmitted strength, T(*m*), such that the intended strength or significance of a message can be predetermined at the sink node.

$$T(m) = I(m) + (h_m * \quad Cp) \tag{4}$$

It is important to note here that while the transmitted strength is positive, the intended strength can be negative. The practical implication of this is that unless the message is correlated with other messages, the strength of the message can reduce to zero during propagation toward the sink node. The message is simply terminated at this point, i.e. it is not propagated any more. As already mentioned, this allows two results to occur 1) weak messages that are uncorrelated can die off - as desired to model the biologically inspired properties, leading to 2) weak messages which die off do not cause the network to expend more energy in relaying and transmitting them. Result 2) saves precious wireless sensor node energy, *especially in critical nodes near to the sink node, which commonly lose energy fastest due to network congestion*.[2]

In actual application, it should be possible to adjust the system such that most messages would be set to die off before reaching the sink node unless they are correlated. This would ensure that only the most relevant information would be included for analysis. Very strong messages could be assigned enough transmitted strength such that they guaranteed reach the sink node with at least some intended strength. This is because the amount of decay can be predetermined based on the hop distance to the sink node and the unknown message correlation will only strengthen a message.

By adjusting the relative values of these two constants, that of correlation and that of propagation, it is possible to “tune” the network, increasing or decreasing the likelihood that messages will reach the sink node under certain cases. This could even be made into an adaptive process.

It should be noted that assigning an intended strength to a message can be performed by the originating node via a simple look up or extrapolation table. For example, in a geological monitoring context, the soil moisture content can range from 0% to usually about 50%. This could be linearly mapped onto a statistical strength of 0 to 1, such that a data reading of 25% moisture content is given a statistical strength of 0.5 and a data reading of 40% moisture content is given a statistical strength of 0.8. Common real world non-linear properties and effects can also be modeled via a look up table and an interpolation method. In general, the larger the intended strength, the greater the likelihood the message has of reaching the sink node.

3 Message correlation

As previously mentioned, an aggregating or correlating function is also needed to implement the boosting effects of message consensus and correlation.

Let there be a rule of correlation (correlation function) such that the new strength of message A when correlating with message B is given by

$$s_{n,new}(A) = s_n(A) + (C_c * s_n(B)) \tag{5}$$

and

$$s_{n,new}(B) = s_n(B) + (C_c * s_n(A)) \tag{6}$$

where C_c is the correlation constant (preferably between 0 and 1), an where n is the network level that the correlation is occurring at (increasing n is towards the sink node). These functions follow the property that correlation of each message is proportional to the strength of the other message. An analogy for this can be seen by considering two football (soccer) players. If a strong player meets up with a weaker player, then they both benefit. But the weaker player will benefit much more from the assistance of the strong player than the stronger player will benefit from the weaker player. This relationship is followed in the above rules.

It is also essential that this correlation function follow a property of “fairness”. “Fairness” can be defined by the condition that if two data messages transmitted from two different parts of the network are correlated at a node some distance from the sink node, and each are then propagated on to the sink node, then their strengths at the sink node should be identical regardless of the distance from the sink node at which they are correlated at. In other words, identical message information broadcasted from two different nodes at a differing number of hops from the sink node should have the same statistical strength at the sink node.

For example, the network would be “fair” if the strengths at the sink node of the messages transmitted by some originating nodes A and B were the same regardless of if they were correlated three hops from the sink node or if they were correlated five hops from the sink node. Again, this ensures that there is no non-uniformity involved in correlating at different parts of the network. Otherwise, messages originating near the sink node would have an unfair advantage over messages originating far from the sink node, due to the propagation decay, and would be weighted much heavier in the ensuing data analysis.

The above functions are not exactly "fair" as defined previously, due to small differences that accumulate as the messages propagate. They can be made fair by subtracting a correction term

$$\text{Correction} = D_{sn} * (0.01) \quad (7)$$

where D_{sn} is the distance to the sink node from the level of correlation. Thus, the correction amount is a relatively small number that can be predetermined. This ensures that the correlation is "fair" or equal for the same data messages when they are correlated at any levels from the sink node.

This property of fairness of correlation is necessary because otherwise, the correlation of two messages would be dependent upon the distance from the sink node they were correlated at. This could be helpful in some cases in which it is desirable that network nodes closer to each other boost each other more due to correlation, but is most likely harmful because it breaks the mathematical symmetry. This topic is left for further development and clarification at the moment.

3.1 Simple example of correlation

If a message A has a strength of 0.5 at the node where the correlation is occurring and if message B has a strength of 0.2 at the same node then the new combined strength for message A is given by

$$S_{n-1}(A) = S_n(A) + (C_c * S_n(B)) \quad (8)$$
$$= 0.5 + (0.1 * 0.2)$$
$$= 0.52$$

where C_c = 0.1 and the new correlated strength for the message B is

$$S_{n-1}(B) = S_n(B) + (C_c * S(A)) \quad (9)$$
$$= 0.2 + (0.1 * 0.5)$$
$$= 0.25$$

where $C_c = 0.1$.

Note that the strength of message B increased more than the strength of message A. Also, the index of S(A) is defined to decrease as the message approaches the sink node, with the index at the sink node being 0.

3.2 Example of correlation and propagation

Let the propagation constant be C_p = 0.1 and let the correlation constant be C_c = 0.1. Also let message A be originally transmitted from a node five hops away from the sink node with an intended strength at the sink node of 0.3. This gives a transmitted strength of 0.8. Let message B be originally transmitted from a node seven hops away the sink node with an intended strength at the sink node of 0.5. This gives a transmitted strength of 1.2.

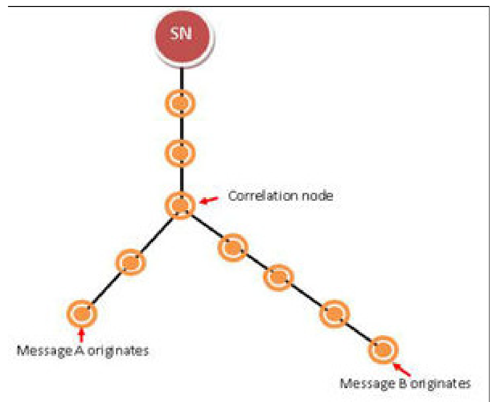

Figure 2 – Correlation of Messages A and B at a Node Three Hops from the Sink Node

Then if we define the correlation of these two messages occurring at a common node 3 hops away from the sink node, the following occurs:

1. Message B propagates four nodes to the correlation node. The new strength of message B is now its original strength minus the loss due to propagation.

   $$S_3(B) = 1.2 - (C_p * 4) \quad (10)$$
   $$= 1.2 - 0.4$$
   $$= 0.8$$

   Similarly, message B propagates 2 hops to the correlation node and the new strength of message A becomes

   $$S_3(A) = 0.8 - (C_p * 2) \quad (11)$$
   $$= 0.8 - 0.2$$
   $$= 0.6$$

2. At the correlation node, the correlation rule is applied. Then the new strength of message A that is propagated towards the sink node is given by

   $$S_{3,new}(A) = S_3(A) + (C_c * S_3(B)) - (0.01 * 3) \quad (12)$$
   $$= 0.6 + (0.1 * 0.8) - (0.01 * 3)$$
   $$= 0.65$$

where 0.01 is the correction factor defined earlier.

Similarly the new strength of message B is

$$S_{3,new}(B) = S_3(B) + (C_c * S_3(A)) - (0.01 * 3) \quad (13)$$
$$= 0.8 + (0.1 * 0.6) - 0.03$$
$$= 0.83$$

Each of these messages thus continues to propagate towards the sink node, such that the strength of message A at the sink node, node 0, is

$$S_0(A) = 0.65 - (Cp * 3) \quad (14)$$
$$= 0.65 - (0.1 * 3)$$
$$= 0.35$$

and the strength of message B at the sink node will be

$$S_0(B) = 0.83 - (Cp * 3) \quad (15)$$
$$= 0.83 - (0.1 * 3)$$
$$= 0.53$$

One thing to note here is that without correlation, the strength of message A at the sink node would be 0.3, and similarly, message B would be 0.5. Thus, correlation boosted the strengths of the messages.

Note that due to "fairness", the received strength of the two messages will not change due to correlating at different hope away from the sink node ie. the same strength at the sink node will be obtained if correlation occurs two hops or six hops from the sink node. With a greater number of nodes and proper timing of the network via tuning the C_p and C_c values, the likelihood of the messaged reaching the sink node can be adjusted until the desired balance of the forces of decay and correlation occurs.

Similar cases can be constructed which :

1) show that messages which would ordinarily die off due to decay can be kept alive through correlation and
2) messages that are uncorrelated will die off.

4 Conclusions

An initial biologically inspired propagation and data correlation scheme has been developed and tested. The primary target of demonstrating the principles that many weak messages can correlate to strengthen each other and a few strong messages can correlate has been maintained. The system allows a natural type of correlation that is proportional to the strengths of the messages and also allows the messages to propagate with a nature mimicking decay. These two opposing forces of message decay and correlation have been successfully simulated with generic cases. Adjustments have been made for fairness of correlation from the sink node and fairness of transmission distance from the sink node, yielding a mathematically balanced system.

Concerning drawbacks, there is the possibility that data from one part of the network could not reach and correlate with relevant data from another part of the network. But if the network is structured correctly as per the application, then nodes that are closer together physically would also be closer together statistically and could be made part of the same network branch.

This type of system is also restricted to directed networks and would be difficult to implement in ad-hoc mesh networks for example.

While simple simulation of correlating two nodes has been performed in Matlab, yielding favorable results that suggest that this process is scalable to aggregation of n nodes at any single node and that large multi-branch directed networks can be built following this model, tremendous opportunity for future work exists.

The next phase of work is to scale the system to include the correlation of n nodes at any one node. This will enable the testing of the algorithm in full network simulations that are likely to be encountered in real life, such as forest fires and landslides as in the WINSOC scenario. Large and small networks with random and non-random data and the expansion to multiple data variables for each message can also be evaluated. The energy efficiency could then be compared to other data transmission and aggregation schemes.

There is scope for investigating the mathematical relationships between C_p and C_c, the constants of propagation and correlation. There should also be a "balanced" state, in which a medium strength message (50%) from a medium number of nodes would have a medium (50%) likelihood of reaching the sink node.

Other functions of propagation and correlation are also possible. Rules of propagation following a squaring pattern have also already been investigated to some extent. Other possibilities such as decaying the message if the correlation is below a certain level could also be studied.

This correlation and decay method can also be applied to the rate of change of data, where a greater rate of change yields a greater strength or statistical significance to the data. This then yields the effect that quickly changing data will be deemed most important and will be much more likely to reach the sink node. This could give another way of aggregating the statistically important data and also provide a consensual method of determining threshold and alert levels [4, 3].

5 References

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