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SIGNAL PROCESSING FOR SENSOR NETWORK

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Abstract: Sensor network is hot area in modern day communication system. Monitoring or tracking of moving objects is one of the challenging problems in today's world. Sensors are used in such type of application. But limited power in sensors makes this task difficult. So, there need energy constraint signal processing in sensor network This paper focuses on how the sensors in the sensor network can sense, estimate the position of the target and track the target, as well as, use its resources optimally. This paper is a survey on signal processing (some IEEE papers) for sensor network.

1. Introduction to Sensor Network

Sensors are sophisticated devices used for sensing the phenomena (temp., intensity of earthquake etc.) or detecting the targets (moving vehicles, individuals etc.). So, there may be many types of sensors depending upon their applications, e.g. seismic, passive infrared intrusion (PIR), magnetic sensing device, still video cameras, acoustic microphone arrays etc. Sensor may be stationary or mobile. The individual sensor can share the information with its neighbors and also with the user via a processing unit (sink). Thus the individual sensor can be grouped to do some particular task or multiple tasks. So, it is needed to realize a network of sensors called sensor network. This sensor network may be used in military application, health, security, surveillance etc.

(i)Networking of sensors:-

Sensors are deployed in the region called "Sensor field", where we want to sense or track or detect the target. So, each sensor must have capability for sensing, as well as transmitting the data to their neighbors. This means, each sensor can be activated; it can transmit data to its neighbors and also can be able to communicate with the user through centre processing location (Sink) [1]. This is illustrated in fig 1a.

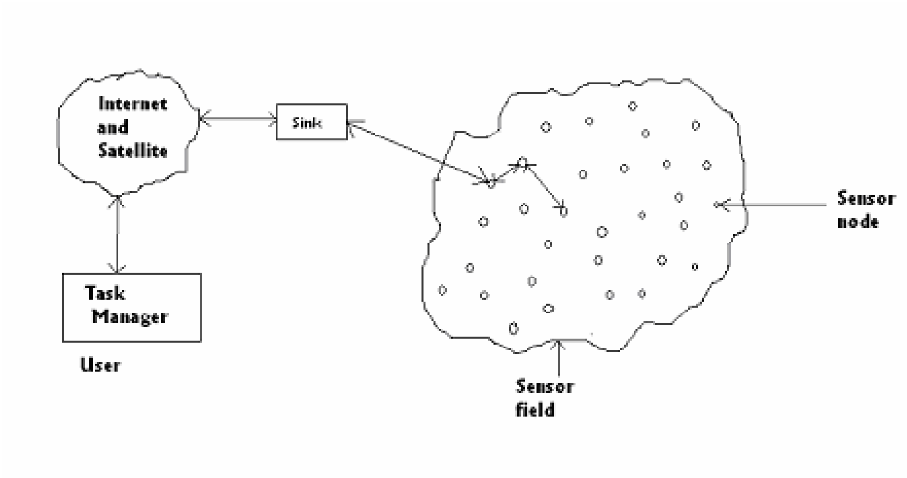


Fig 1a. Sensors deployed in sensor field

There may be other type of sensor network which includes less no of sensors (few tens of sensors) for medical application or tracking an enemy vessel in territory.
But here we consider the network of a large number of micro sensors (hundreds to several thousands)

(ii) **Protocol Stack**:

The protocol stack used by the sensor network and sink, is similar to that of computer network [1].
Here each of the layers and protocol used in those layers are illustrated briefly.

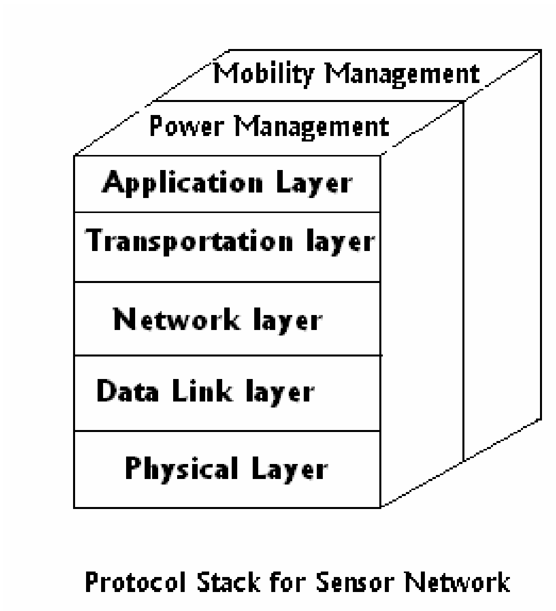


Fig 1b.

Physical layer:

This is the ground layer of the network protocol stack. The task of this layer is to select the frequency, generate the carrier frequency, detect the signal and modulate it.

So, signal propagation effects, modulation schemes for effective communication, are important things in this layer.

Binary or M-array modulation scheme can be used in this layer. Low power spread spectrum modulation can also be used [1].

Data link layer:

This layer is above the physical layer and below the network layer. The main task of this layer is multiplexing of data streams and to detect data frame. This layer also establishes point to point or point to multipoint connection. The Medium access Protocol (MAC) used in this layer must be different.

Sensor networks must be designed in such a way that power consumption is less. Unlike cellular system, the power sources in sensor network can not be replaced or recharged. So, MAC protocol used in this layer must be different from that case of cellular system. Self Organization Medium Access Control for Sensor Network (SMACS) protocol can be used in this layer.

Self Organization Medium Access Control for sensor Network is illustrated in [2]. In this network, nodes in the sensor networks are assumed to have the capability of turning its 'radio' on and off and also able to tune the carrier frequency. 'Channel ‘or Time division multiple access (TDMA) slot is assigned to a link just after its existence is discovered. Here each link will operate on a different frequency to avoid collision during transmission or receiving.

(a) In this protocol, when a node (say node 1) is 'waken up', it listen to the 'channel' for a certain time. If it does not receive any response for that time interval, it sends one message (invitation) by the end of its listening time.

(b) The other nodes which are activated in between, will receive that message. And as soon as they receive it, they also send reply to that node. Then the node 1 will receive those entire message if those 'reply' do not collide. After that, node 1 will select one node (say node 2) whose reply is received first or depending on the highest signal level of the replies it received.

(c) In third step, it will send another message to all the nodes informing which node it selects. All the nodes, except the node which is selected, turn off their ‘radio’ for some time and after some time those nodes repeat the searching procedure.

So, finally one link between node 1 and node 2 is established. And they start receiving and transmitting each other for two time slot (One for receiving and another for transmitting). And these time slots will be repeated periodically every certain fixed time interval (T_{frame}) called super frame. This T_{frame} is fixed for each node. When any new node is found, super frame will be filled with another two time slots for that. The main characteristic of this protocol is to use 'non synchronous' assignment in time slot.

After a link is established, a node knows when to transmit and when to receive. Hence, it will turn off its radio in its idle state.

Network layer:

The network layer of the sensor network is quite different from other networks. So a special type of routing protocol discussed in [1] can be used here.

Energy efficient routes discussed in [1] consider the available power (PA) in the nodes and the energy required (α) to transmit data from one node to another.

Node S (Fig 2a) is the source and it sends data to the sink. There are 4 routes from sink to source.

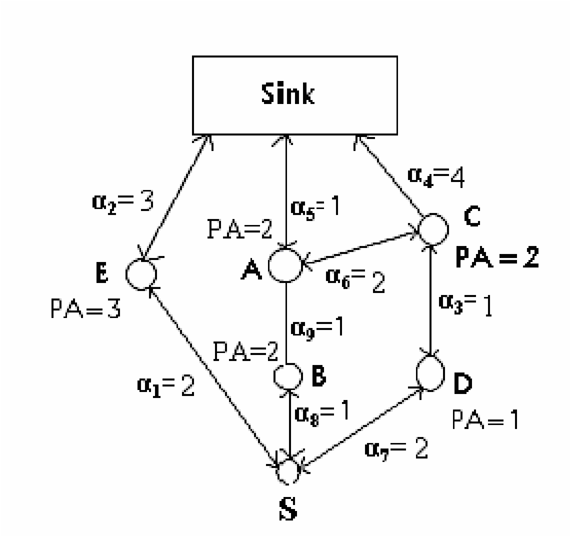


Fig 2a.

Route 1: Sink-A-B-S   Total PA = 4
Route 2: Sink-E-S   Total PA= 3
Route 3: Sink-C-D-S Total PA = 3
Route 4: Sink-C-A-B-S Total PA = 6

Maximum PA Route:

Route 4 has maximum PA. But it is nothing but the extended path of the *Route 1*. So, it is not power efficient.

Minimum hop (MH) Route:

Here *Route 2* has the minimum hop. So, route 1 will be selected when minimum hop route is considered.

Maximum minimum PA node Route:

Route 2 has minimum maximum PA.

Minimum energy Route:

Route 1 is minimum energy route.

Data aggregation:

Sometimes it is effective to aggregate the data of an 'attribute' of a ‘phenomena’. In the picture shown below, node 1 and node 2 are used to sense the same phenomena and send the data to the node 4. Here, node 4 aggregates the data from node 1 and 2 and transmits it to the next node, instead of sending the data collected form node 1 and 2 separately.

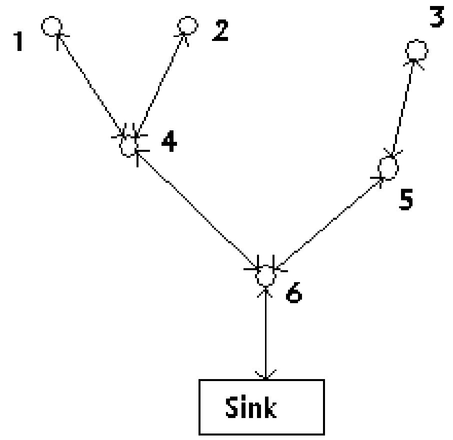


Fig 2b.(Data aggregation)

Transport Layer.

It is above the network layer and below application layer. This layer is responsible for communication with other networks through internet. TCP protocol used for computer network may be applicable here. But UDP-type protocol will be preferred during communication between sink and sensor nodes for limited memory of sensor nodes.

Application layer:

Application layer is important when communication is needed between multiple networks. Protocols used in this layer are Sensor management protocol, Task Assignment and Data Advertisement Protocol (TADAP) and Sensor Query and Data Dissemination etc [1].

2. Collaborative Signal Processing:

(i)**What is collaborative signal processing?**

By signal we understand 'something' that signifies some occurrence of events of our interest. It may be deterministic in nature or may not be. But it conveys some information. Processing means understanding that signal, or to modify (transformation, selective retention) that signal in order to extract the information it carries. So, signal processing means to process the signal to extract information that it carries. “Collaboration” means “co-operation” or “working together”. Hence, collaborative signal processing means to process the signals received by a group of elements. In case of sensor network, these elements are sensors and the information is “the location of the target(s)”.

(ii) Why is it needed in Sensor Network?

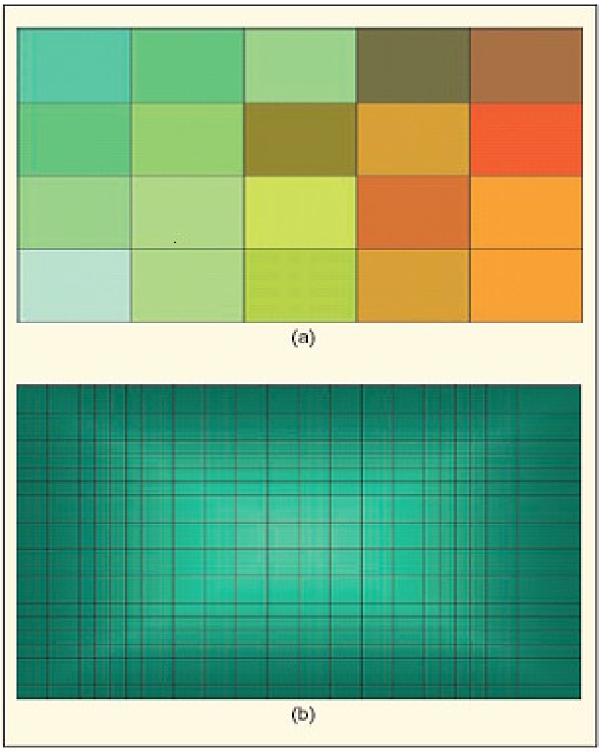
We know that “Unity is strength”. The importance of collaborative signal processing lies in this line. In order to achieve a bigger goal, information must be shared. In case of sensor network, main critical thing is power and the 'goal' is to detect, identify and track any target. Again sensors are powered by fixed energy sources which are supplied at the time of network forming. So, 'limited power' is key factor here. Receiving, transmitting, and processing of data is to be done with that limited power.

Each sensor must process the signal for certain time period. Again it may detect only the local events. So, it must share the information with other. Hence, collaborative Signal Processing among sensor-nodes is needed to fulfill the goal.

(iii) Sampling in space and time [3]:

The signal from each object is time varying and that signal must be sensed by the sensors. Sensors are densely deployed in a region. This can be thought that nodes sample the “time varying signature field” spatially. The total number of sensors in the sensor field will depend upon the changing rate of the “signature field”. Again each sensor will sample the signal (time sampling) at a rate depending upon the bandwidth.

Now, one may consider moving objects as “moving peak” in the “spatial signature field”. So, they may think the entire space time region, consisting of a number of space time cells, where the 'space time signature field’ is constant. The size of this cell depends on the velocity of moving target.



(a) Uniformly sized space-time cell
(b) Non uniformly sized space-time cell

Fig 3. (taken from [3])

The figure (taken from [3]) above illustrates this. Here different shades indicate the variation of the “signature field”.

3. Source localization:

Sensor networks are designed to sense “something”. This “something” is 'target' or source. So, sensors in sensor network need to detect the target more specifically 'target location'

For the near field acoustic or seismic source, the received signal is curved and that curvature depends upon the distance. For far field source, this wave front becomes planner and parallel. So, for far field, direction of arrival (DOA) can be estimated by an array of equally spaced sensors, looking at the time delay of the signal [4]. In case of near field source, location can be estimated from the relative time delay of the source signal.

But there are many factors which stand in the way off estimating the location of the source. Temperature, wind velocity has effect on the propagation speed.

In case of seismic source, propagation speed is medium dependent. In case of sound wave, energy received at any point is inversely proportional to the distance from the source. In case of seismic propagation, reverberation in inhomogeneous medium makes the localization problem difficult.

(a) Localization based on energy [3]:

Here, it is considered that the target signal attenuated exponentially with the distance. Let $y_i(t)$ is the received energy at the i^{th} sensor [3]. Then

$$y_i(t) = s(t) / \| r(t) - r_i \|^{\alpha}$$

Here, $r(t)$ is the unknown source co-ordinate which is to be determined and r_i is the co-ordinate of the i^{th} sensor. $s(t)$ is the source signal energy.

$$\rho_{ij} = y_i(t) / y_j(t) = \| r(t) - r_j \|^{\alpha} / \| r(t) - r_i \|^{\alpha}$$

ρ_{ij} is the ratio of the two energy received by two sensors i and j.

So, if there are n numbers of sources or targets, we will get ${}^{n}C_{2}$ number of ratio out of which (n-1) number are independent.

The loci of the target for each ratio will be a circle. So, all these circles will intersect at a single point which will be the location of the target.

So, here the problem is to solve a least square problem

$$J(x, y) = \sum_{i=1}^{M} \| (x - o_{i,x})^2 + (y - o_{i,y})^2 - \rho_i^2 \|^2$$

Where $(o_{i,x}, o_{i,y})$ are the centre co-ordinate and ρ_i is the radius of the circle of i^{th} ratio, M is the total no of ratio.

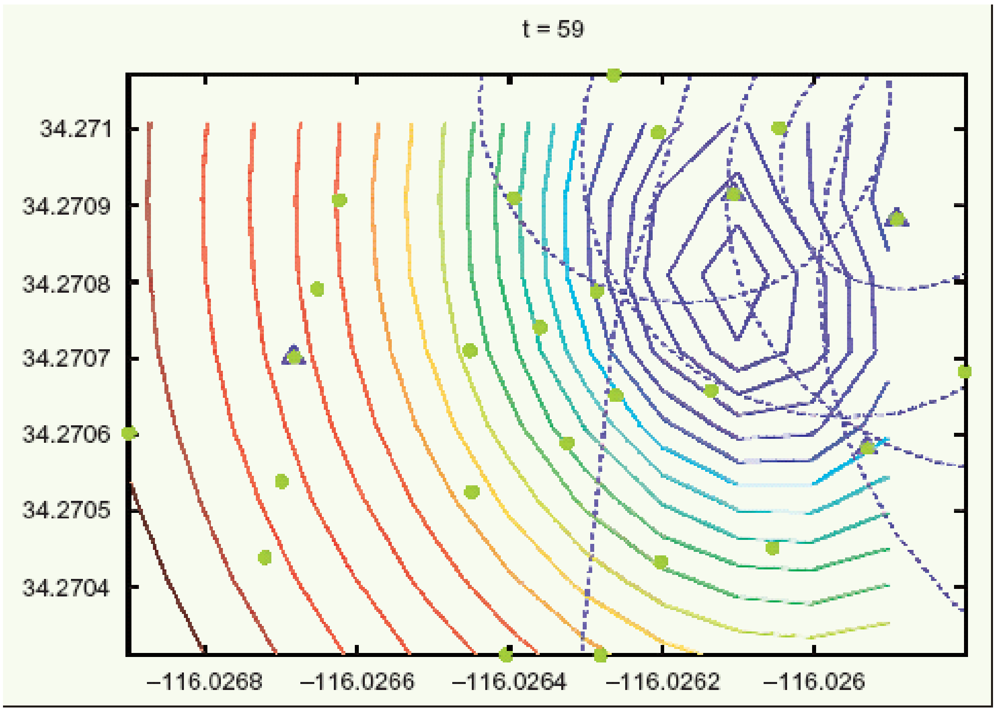


Fig 4(taken from [3])

This is illustrated in fig 4 (Taken from [3]). The dotted circles are the loci of the source location.

(b) Source localization in the near field (Based on maximum likelihood):

This is illustrated in [5]. Here there are M no of sources and their locations are to be estimated by R no of sensors. The no of samples taken at each sensor is L.

Let $x_p(n)$ denotes the data collected by the p^{th} sensor at time n.

So $x_p(n)$ will be given by,

$$x_p(n) = \sum_{m=1}^{M} a_p^m s_0^m (n - t_p^m) + w_p(n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

n=0,1 ,2 …..L-1,

Where,

a_p^m the gain of the signal from m^{th} source received by the p^{th} sensor.

s_o^m the signal strength of the m^{th} sensor.

t_p^m the time delay of the signal from m^{th} source to p^{th} sensor.

w_p is the Gaussian noise with zero mean and variance σ^2

Time delay $t_p^m = \| r_{sm} - r_p \| / v$

Where

r_{sm} is m^{th} source location.

r_p is the p^{th} sensor location.

v is speed of propagation in length unit per sample.

So, time delay between p^{th} and q^{th} sensor will be given by:

$$t_{pq}^m = (t_p^m - t_q^m) = (\| r_{sm} - r_p \| - \| r_{sm} - r_q \|) / v$$

Taking N point DFT of the equation (1) we get ($N > \zeta$ where ζ is the maximum time delay between a pair of nodes.)

$$X_p[k] = \sum_{m=1}^{M} a_p^m \exp(-j2\pi k t_p^m / N) + W_P[k]$$

$$d_p^m[k] = a_p^m \exp(-j2\pi k t_p^m / N)$$

And $S_0[k] = [S_0^1[k] S_0^2[k] .... S_0^M[k]]^T$

$$X_p[k] = [d_p^m[k] d_p^m[k] .... d_R^m[k]] S_0[k] + W_P[k]$$

Now let

$X[k] = [X_1[k] X_2[k].,.....X_R[k]]^T$ (super script T denotes transpose)

$$d^m[k] = [d_1^m[k] d_2^m[k] .... d_R^m[k]]^T$$

$$D[k] = [d^1[k] d^2[k] .... d^M[k]]$$

Then

$$X[k] = D[k] S_0[k] + \eta[k]$$

$\eta[k]$ is noise spectrum vector.

The source location and source signal can be estimated by minimizing $\| X[k] - D[k] S_0[k] \|^2$

4. Information Driven Sensor Network:

In [6], they illustrate information driven dynamic sensor network. They optimize the "information utility of data" for a given cost of communication. Sensor network can be designed to track a "moving phenomena" in sensor field or to monitor a large no of events simultaneously. Sensors also may have to detect "low-observable events". Data collected from many sensors, involving to detect the same phenomena, can be aggregated to improve accuracy. So, collaboration between sensors is needed.

Now the questions which automatically come are 1) "Who should sense? " 2) "What is to be sensed?" and 3) "Who should pass the information?" [6]. So, we need collaborative signal processing to answer these questions. 1^{st} question is related to "Sensor selection". 2^{nd} question is related to "Target".

In case of detecting some changing phenomena, the sensor around which the changes take place must be selected. And in case of tracking an object, the sensors whose locations are predicted by optimizing the information utility and cost, are needed to be selected.

In [6], this is illustrated using an example of tracking a moving vehicle in a 2-D sensor field. A user query, "to report the position of the vehicle every 5 min", enters the network at node Q (in the fig 5). Here, the sensors are assumed that it can sense local events and also can estimate the cost of sensing, processing and communication of data with other nodes in that sensor field. It is illustrated in fig 5.

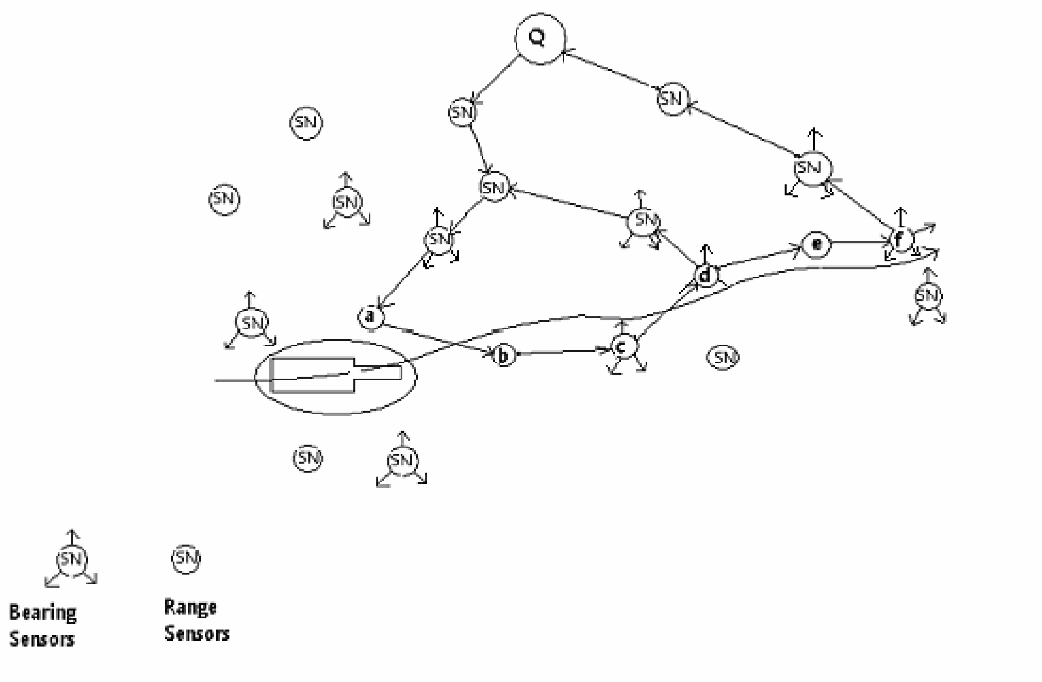


Fig. 5

Suppose ‘a’ has the initial information of the vehicle state $x_{a.}$ It then combines this current state with sensor characteristics of its neighbors. And calculate the next best sensor.

Here, node ‘a’ find node ‘b’ as ‘best next sensor’ and transfer the state information to node ‘b’. Node ‘b’ combines its measurement (z_b) with the previous state x_a and finds the next best sensor ‘c’. Similarly node ‘c’ finds node‘d’. Node ‘d’ sends the current state to the node ‘Q’. Node‘d’ also finds the next best node ‘e’ and node ‘e’ finds node ‘f’.

Node ‘f’ sends the current state to the node ‘Q’.

To optimize the problem of selecting the sensor which can give best information at low cost, an objective function is defined [6]

$$M(P(X / Z_{1,}Z_2 \ldots\ldots., Z_j)) = \alpha\Phi_{utility}(P(X / Z_{1,}Z_2 \ldots\ldots., Z_j)) - (1-\alpha)\Phi_{\cos t}(Z_j)$$

$\Phi_{utility}$ = Information utility measure.

$\Phi_{\cos t}$ = Cost of communication

Z_j is the measurement by the new sensor.

X is the state of the target to be estimated.

α is the relative weight.

Here the measurement by the new sensor is combined with the present estimation $P(X / Z_{1,}Z_2 \ldots\ldots., Z_{j-1})$ and the result $P(X / Z_{1,}Z_2 \ldots\ldots., Z_j)$ is called the belief state.

Leader node of the network will hold the current belief state. The leader node may be stationary or the leadership may move from one node to another in the sensor field.

5. Sensing, tracking using relation between objects

The sensors deployed in the sensor field, are powered by fixed battery. Once the network is formed, one neither can replace nor charge the battery. So, the software controlling the sensor network must be such that it uses the resources optimally. In [7], it is done cleverly by forming relation between objects reducing the use of resources while achieving the same goal.

(i)Tracking of objects forming relation:

In [7], tracking of the objects is considered in two cases. In case 1(fig 6a.), they consider a picture where it is needed to monitor the 'suspicious individual' in a group of people moving around a building. And in the second case (fig 6b.), they consider "military engagement in an open terrain with a few building and ground enemy (*e*) and friendly vehicle (*f*) moving in it." In these two examples, relations between the objects are formed. After that, those relations between the objects are tracked instead of each object separately. For this, the partial information about the environment are aggregated and stored in some nodes, so that any 'global query' can be answered without re-computing the data and thus saving the 'scarce resources'.

In case 1, they form ' >'("Ahead of") relation between the individuals being tracked by the cameras 1, 2 and 3(fig 6a.(taken from [7])). Here, *a*, *b*, *c*, *d*, *e*, *f* are the individuals who are moving inside a building and protection for the individual m is needed.

So camera 1 can detect the relation *b*>*c*>*d*>*e* and camera 2 can detect *a*>*b*. So by aggregating this data, one can find the leader of the group.

In case 2, they form a CCW relation between the sensors, "friendly vehicles" and "enemy vehicles". The sensors, considered here, are PIR (passive Infrared Intrusion) sensors. In the fig 6b (taken from [7]), s1, s2, s3 are the PIR sensors and *e1, e2, e3* are the enemy vehicles. If CCW (*f e2 e3*), CCW (*f e3 e1*) and CCW (*f e1 e2*) implies CCW (*e1 e2 e3*), one can come into conclusion that friend *f* is surrounded by enemies. (Here the relation CCW (a b c) between the points a, b and c is referred to the counter clockwise direction relationship which will be maintained while traversing the triangle formed by those nodes a, b, c).

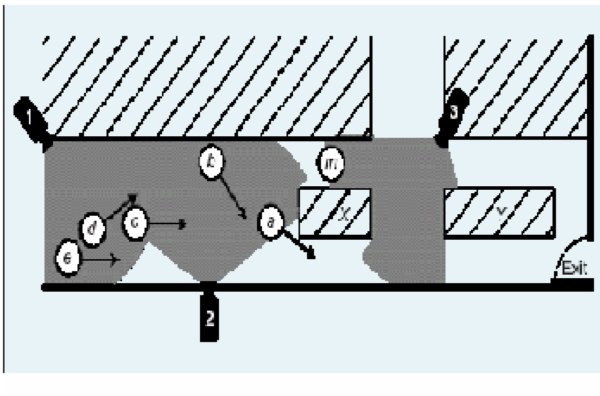


Fig. 6a. (taken from [7])

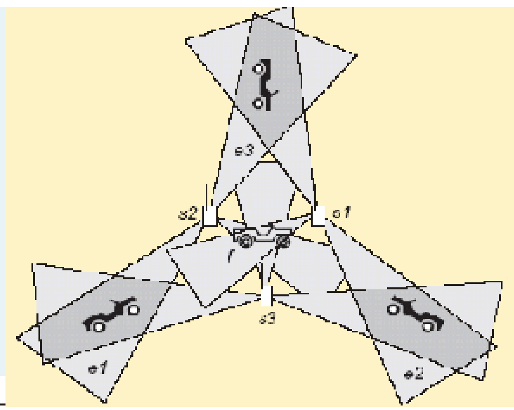


Fig. 6b.(taken from [7])

(ii)Cluster Formation:

Forming of cluster in some application become effective in terms of power efficiency while avoiding duplicate data measured by other sensors. This is illustrated in [7], considering the sensors, being carried by friendly vehicles. The friendly vehicles form some clusters, depending upon their location and cluster radius. One cluster-head will be elected by the each vehicle. The selection of cluster-head may be based on their unique ID.

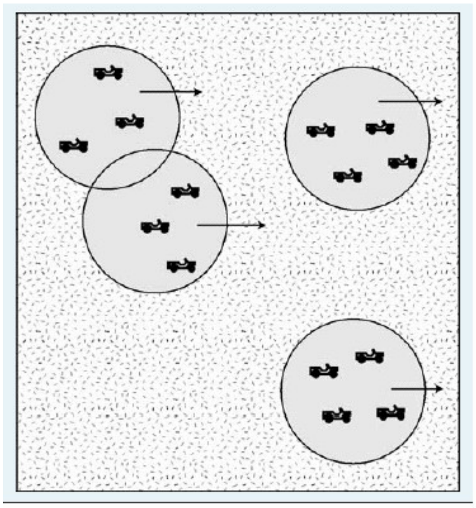


Fig 6c(clustering vehicle)[7]

(iii)Target counting:

By collaborative signal processing the number of targets in a region can be easily estimated. It is obvious that the region must have simple geometric shape or otherwise one have to approximate that region as a simple shape.

In [7], they illustrate it using an example of an area as shown in the fig 6d (taken from [7]). Here each sensor has the capability of sensing, localizing and counting the number of targets in a small region. Now the total area is divided into some small areas (cell). Area of this cell is such that there will be at least one sensor in that cell which can detect the target when it enters into that cell.

So, sensors in each cell can count the total no of targets in that region by “light weight collaboration”. If we think one leader in each cell and the leader in one cell can communicate with other leaders in that row, then after some time when the counting process is over, we will get the following information:

The total no of target in each cell
No of targets in the cells which are at the right side of that cell
No of targets in the cells which are at the left side of that cell

With this information, we can easily estimate the total no of targets in any region within that region.

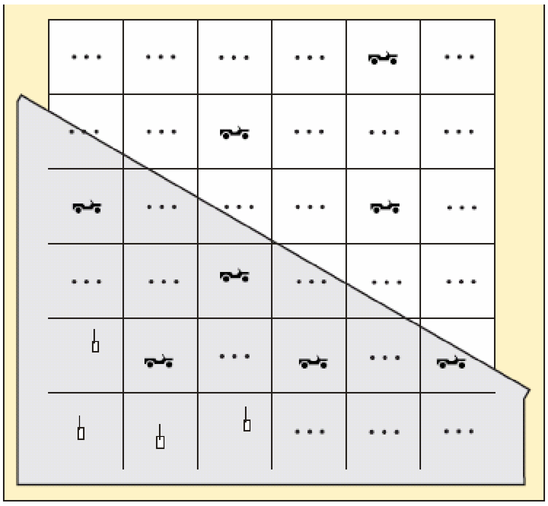


Fig 6d.(Counting of targets in half-space)[7]

(iv)Sensing non local relation [7]:

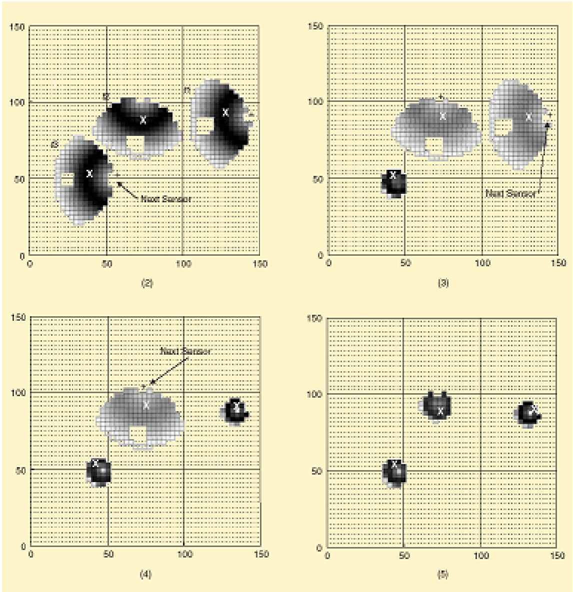
Though in the section 5-(i), the relation is formed between the objects by one sensor which can see all of these objects, it may be happened that one sensor is unable to form the relation. Among the two example in sec 5-(i), in case 1, the camera can see the pairs of objects to form > (Ahead of) relation. But in the second case, the PIR sensor may not see all the three vehicles. In that case, that PIR sensor must take help of other sensors which can localize the target. So, there may be uncertainty in forming the CCW relation in this case.

If Probability (CCW (t1, t2, t3) =TRUE) is close to 1 or 0 then CCW relation will be valid (Here t1, t2, t3 are distribution of the predicted location (belief) of the target. So, if Probability (CCW (t1, t2, t3) =TRUE) isn't close to one or zero, it indicates two things:

(a) The three objects are collinear
(b) Target localization is poor.

In such cases, another measurement must be taken about the target location to reduce uncertainty or the sensor must give a feedback that "I am unable to form the relation", so that manager can take other necessary action.

Fig 7(taken from [7]) illustrates this. Here X is the target location. Shaded area is the distribution of the belief state. And + is the location of the next sensor which can reduce the 'location uncertainty'.



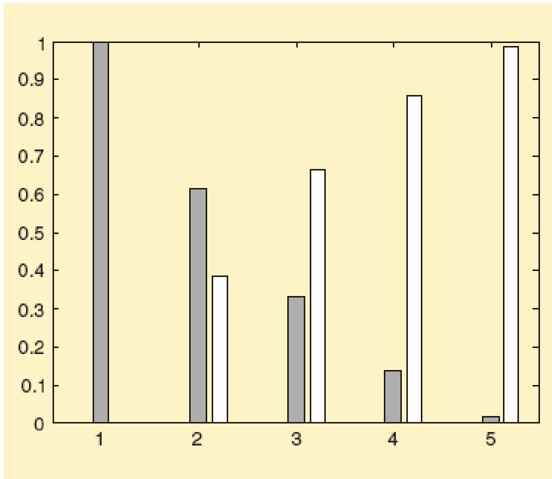


Fig 7 (taken from [7]) Fig 8 (taken from [7])

Fig 8(taken from [7]) illustrates each frame using bar chart. Color 'gray' indicates 'uncertainty' in measurement and 'white' indicates the 'truth of the relation'. From frame 1 to 5, the uncertainty is reduced while frame 5 indicates that 'the relation is formed'.

(v)Incrementally updating information:

Once the relation between objects is formed, that must be updated, so that, it can answer the "global query" at any time. Otherwise at each time, it has to recompute the values. So, when the relation fails, it must be updated. Hence, certification of this validity is needed [7].

Fig 9 (Taken from [7]) illustrates it. Say, we are interested to find the leader. As soon as *d* is going to overtake *c*, *c*> *d* relation fails. But camera 1 can form the relation that *b*> *d*. Camera 2 can form the relation *b*> *c* and *a*> *b*. With this two information camera 2 can come into the conclusion that the relation, "*a* is leader" is valid.

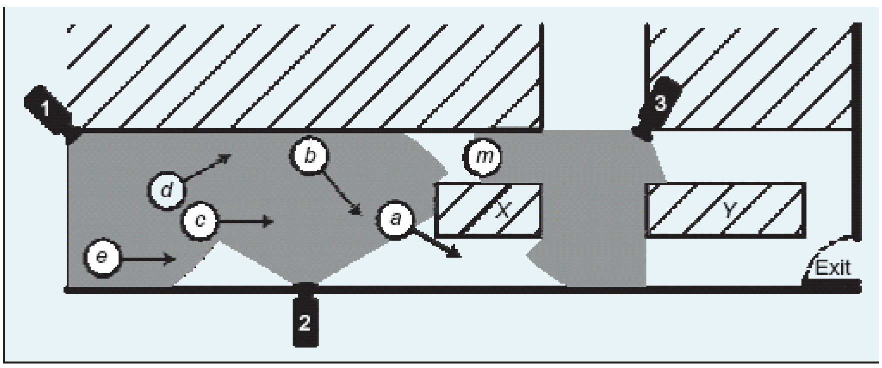


Fig 9(taken from [7])

Conclusion and scope for future work:

In this paper, I've discussed how the sensors in sensor network can locate the target. After that we've seen, how it can track the target optimizing the cost and information utility. And finally it is shown that, if the relation between objects to be tracked, are formed cleverly, it will be possible to save the resources. It's obvious that practical realization will be harder than the theoretical part discussed.

So there will be many challenges regarding theoretical part as well as its practical implementation. Much research work may be carried out in this regards. The research work may be carried out to design an effective algorithm in signal processing which can handle all the problems (limited resources, mobile nodes etc.) Another research work may consider monitoring some events in underwater, space or in some remote places where the events are more difficult to monitor

Acknowledgements

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