Sink Mobility

Basic Task

- A fundamental task of wireless sensor networks (WSNs) is *Data gathering*. It aims to collect sensor readings from sensory fields at predefined *sinks* (without aggregating at intermediate nodes) for analysis and processing.

Basic Task(cont..)

- For a static sink uniform distributed WSN, research has shown that sensors near a data sink deplete their battery power faster than those far apart due to their heavy overhead of relaying messages.

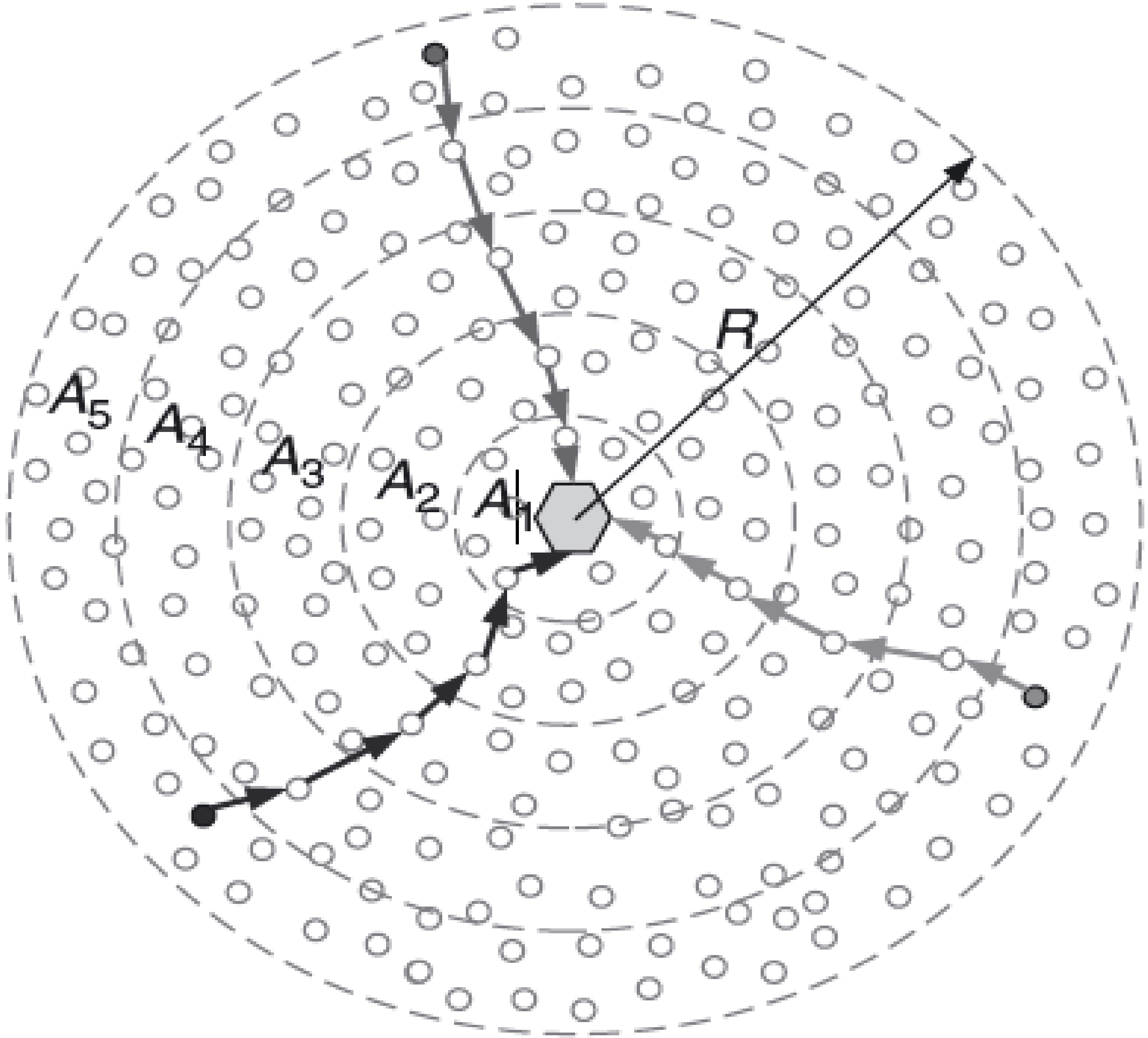


Figure 1. Sensor-to-Sink routing.

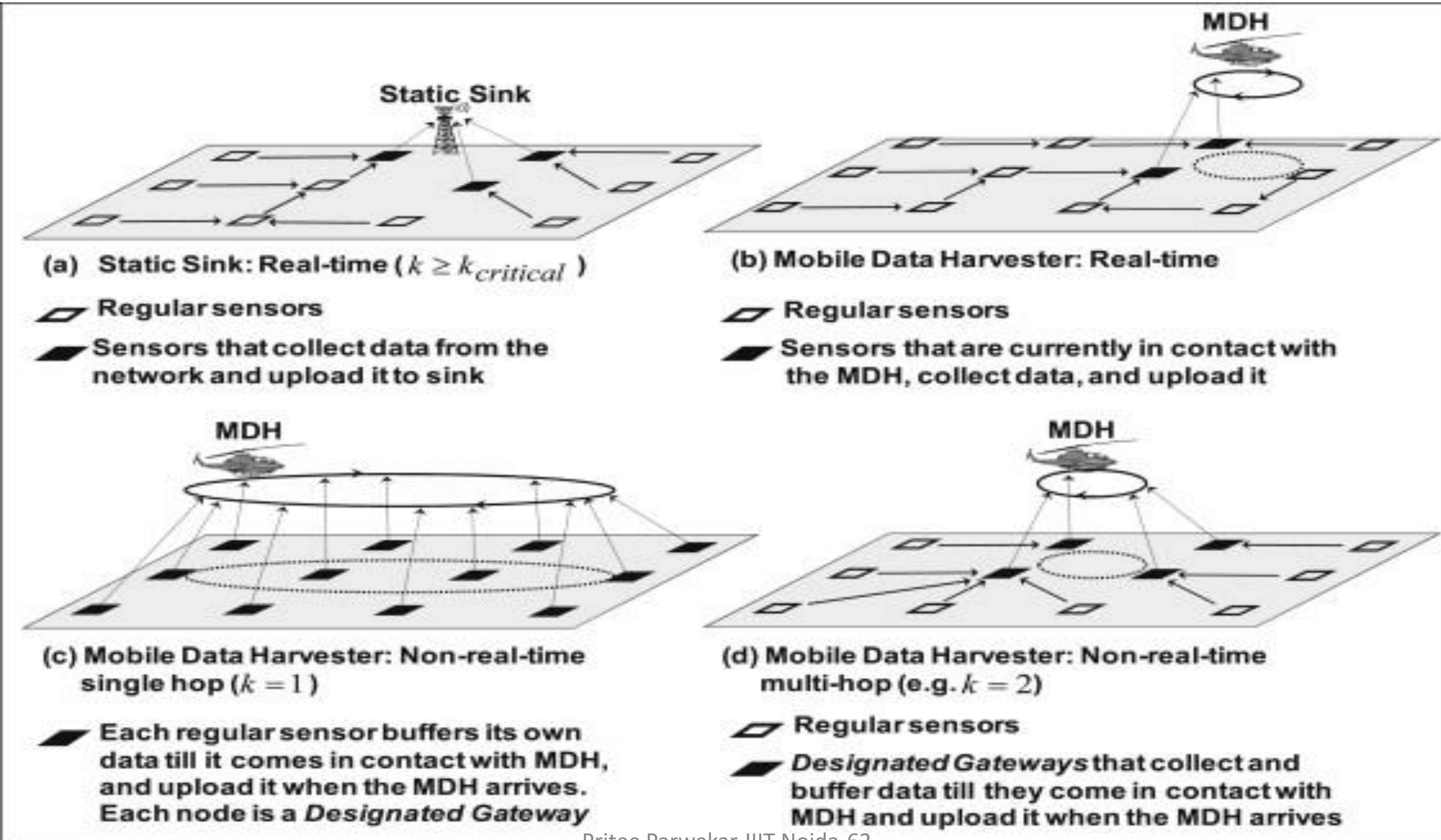
Problems in Sensor-Sink Routing

- Sensors nearby sink are shared by more sensor-to-sink paths having heavier message relay load, and therefore consume more energy.
- This uneven energy depletion causes ***energy holes*** and leads to degraded network performance and shortens network lifetime.

Solutions

- Numerous researches has been conducted to mitigate this problem for both:
  - Static Sink: Power-aware routing and proper use of multilevel transmission radii.
  - non-uniform node distribution.
  - Sink Mobility.

Static and Mobile Sinks



Energy Efficiency by sink mobility

Sink mobility can be classified as :

- *Uncontrollable:* achieved by attaching a sink node on a certain mobile entity which already exists in the deployment environment and is out of control of the network (e.g. an animal or a shuttle bus).

- *Controllable:* achieved by intentionally adding a mobile entity into the network to carry the sink node (e.g. mobile robot or an unmanned aerial vehicle).

Energy Efficiency by sink mobility Delay-Tolerant WSN

- Applications: Habitat monitoring and water quality monitoring.
- Objective: Maximize energy savings for sensors.
- Cons: Data Collection latency.

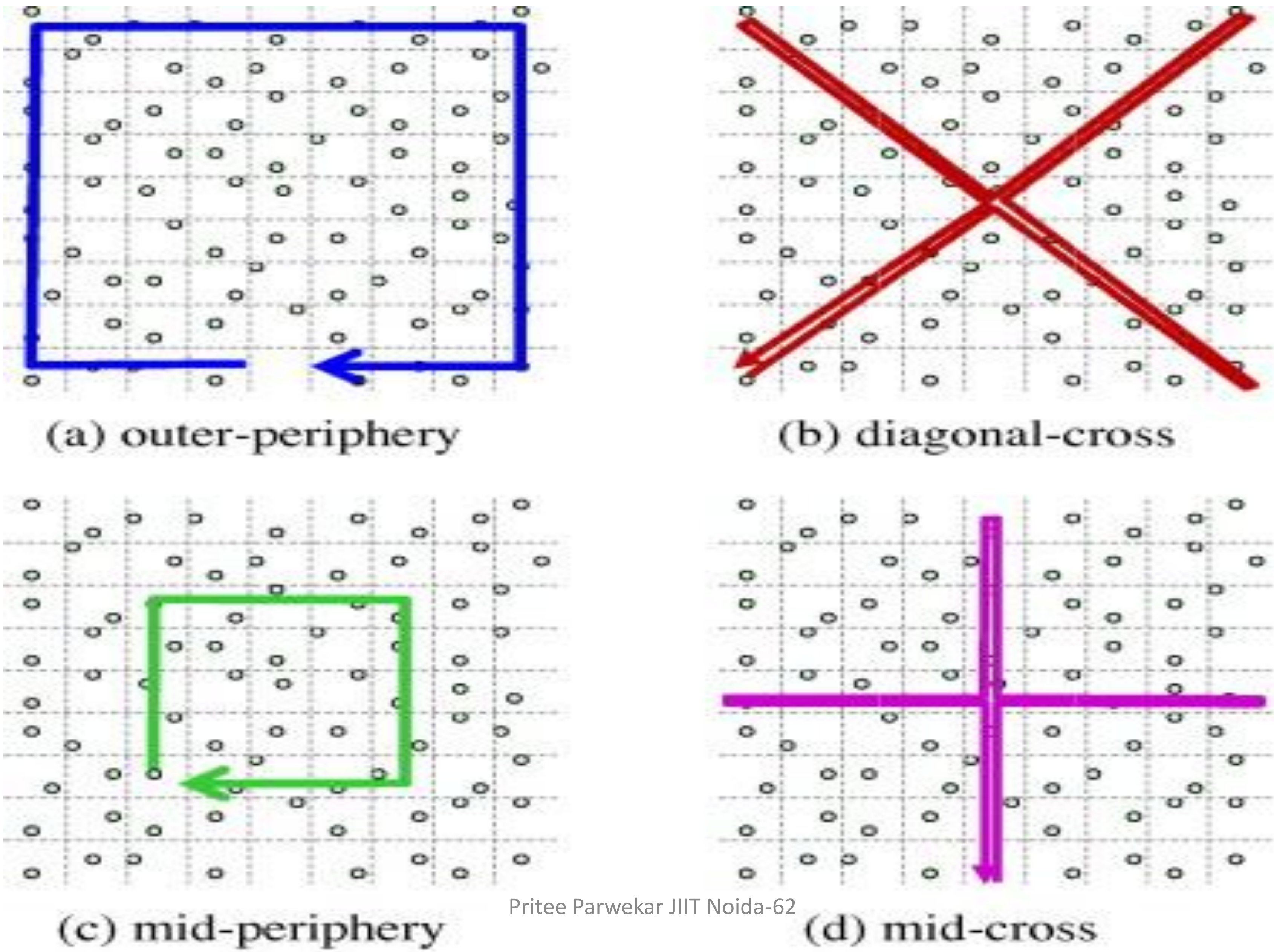
- Data Collection Strategies:
  - Direct-Contact Data Collection.

Direct-Contact Data Collection

- Mobile sink collects data directly from data sources by one-hop communication. Sinks may retransmit data or, if needed, physically carry the data to a fixed base station.

- Concerns: The computation of the best sink trajectory that covers all data sources and minimizes data collection delay.

Path-constrained **mobile sink** trajectories.



Direct-Contact Data Collection

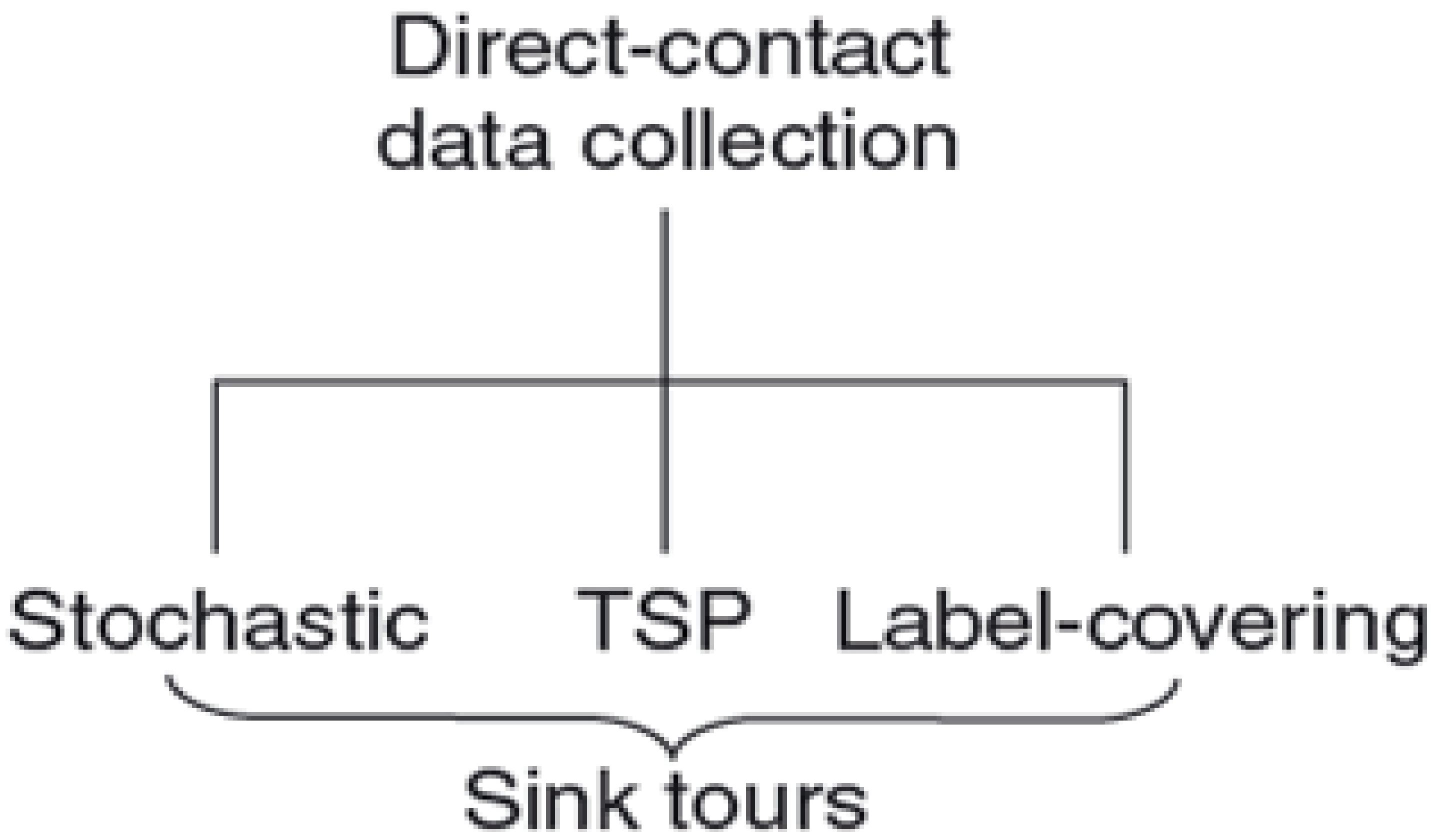


Figure 2. Data Gathering in delay-tolerant WSN – Direct-Contact data collection.

Sink Trajectory Methods

- **Stochastic:**

Shah *et al* [3] considered stochastic sink mobility and proposed a simple data collection algorithm.

- Sensors buffered their measurements locally and wait for the arrival of a mobile sink.
- Energy consumption at sensor side is only due to sink discovery and subsequent data transfer.
- Sink broadcasts a beacon message while moving.
- Sensors monitor the wireless communication channel. Whenever a sensor hears the beacon message it concludes that a sink arrives.

Sink Trajectory Methods

Cons:

- Constant channel monitoring is very expensive.
  - If sinks move along regular path, then sensors can predict their arrival after being allowed a learning curve for their movement pattern.
- Data transfer should start in an intelligent way, if a sensor simply transmits as soon as it discovers the sink, data may not be successfully delivered or may be delivered with many retrials, wasting energy.
  - Data transfer should take place in the time interval with minimum message loss probability, which is exactly around the minimum sensor-sink distance point.

*Sink Trajectory Methods:*Label-Covering:

Sugihara and Gupta [6] *relaxed the requirement for exact one-time visit of the sink to each sensor's communication range*.

– Intuition: Sink's travel time could be long if the length of the intersection of its path and the communication range of each sensor is short.

- Exact one-time visit may not always be a winning strategy. On the contrary, multi-visits together with proper speed control may yield a better solution. The sink simplified the path trajectory problem by reducing search space to a complete geographic graph, where there are vertices at sensors' locations.

Sink Trajectory Methods: Label-Covering:

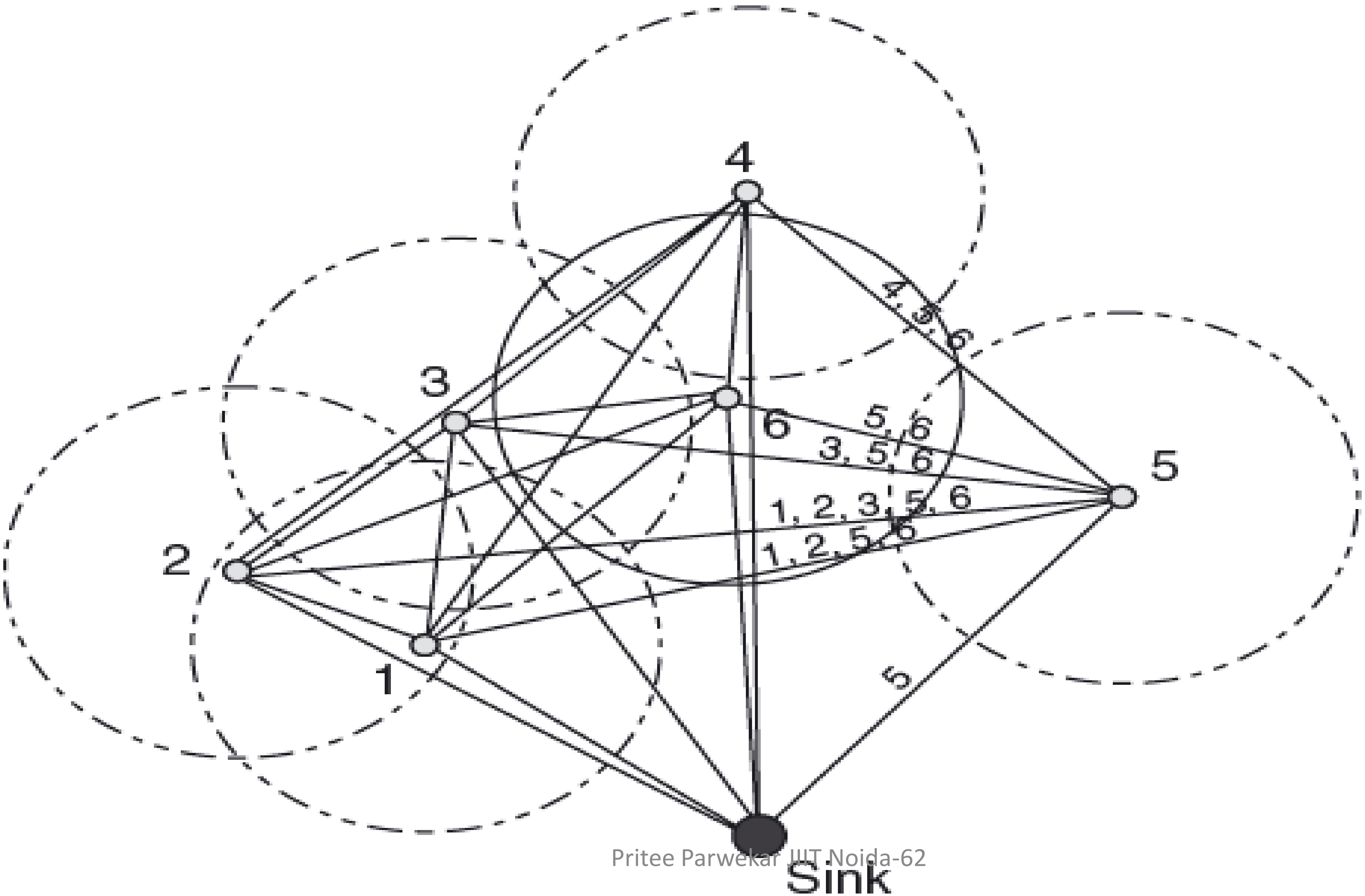
- The sink moves in this graph along edges from vertex to vertex. Each edge is associated with a cost and a set of labels. Cost is defined as Euclidean length of the edge; the label set represents the set of sensors whose communication ranges intersect with this edge.

Sink Trajectory Methods: Label-Covering:

- The objective is to find a shortest (minimum-cost) tour whose associated label set covers all sensors.

- They proved that the shortest label-covering tour problem is NP-hard, and presented an approximation algorithm to solve it. The algorithm finds a TSP tour by any TSP solver. Then, by dynamic programming, it finds the shortest label-covering tour that can be obtained by applying shortcutting to the TSP tour.

Sink Trajectory Methods: Label-Covering:



Sink Trajectory Methods

- **TSP:** With controllable sink mobility and knowledge of sensor locations, data collection delay can be reduced by properly selecting sink trajectory.

Nesamony *et al* [4] formulated the sink traveling problem as a variant of TSP, known as *traveling salesman with neighborhood* (**TSPN**) *where a sink needs to visit the neighborhood of each sensor exactly once*.

  - Intuition: it is sufficient for the sink to be within the communication range (modeled as disk) of a sensor in order to retrieve data from that sensor.

Sink Trajectory Methods

Figure 3 shows the TSP tour (dashed thick lines) and the TSPN tour (thick lines) of four sensors for a mobile sink.

- This algorithm requires that the locations of all sensors are known.
- It first determines the visiting order of the disks. In this process, some ordering constraints may apply (e.g. the disks whose corresponding sensors are about to deplete their battery power have to be visited first in order to prevent data loss). If there are no constraints, then the most intuitive way is to order the disks based on the TSP order of their representative points.

The initial set is composed of the starting point a_0 and the representative points a_i^0 of the *ith* disk C_i.

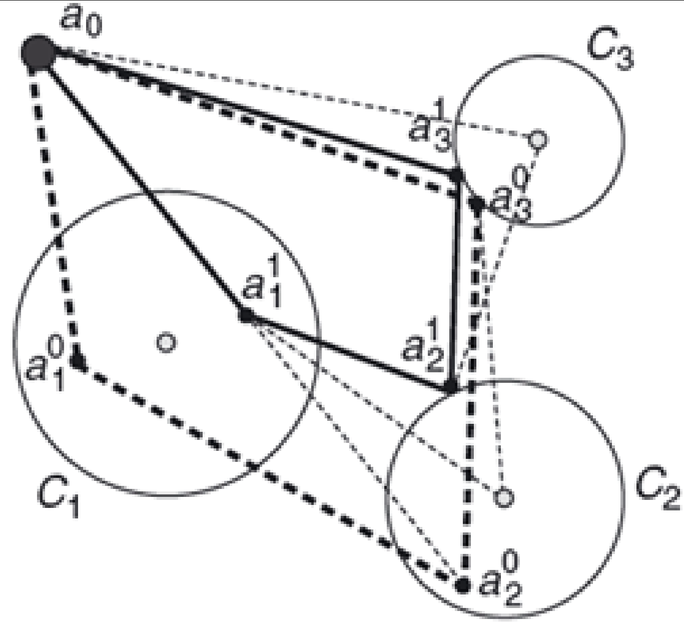


Figure 3. Point set computation.

Computation:

- Line $a_0a_2^0$ intersects C_1 then a_1^1 is any point between intersections; otherwise, a_1^1 is a point on the circumference of C_1 such that $|a_0a_1^1| + |a_1^1a_2^0|$ is minimized.
- Same applied to a_2^1 and a_3^1

Rendezvous-Based Data Collection

- Proposed to achieve trade-off of energy consumption and time delay. Sensors send their measurement to a subset of sensors called *rendezvous points* (**RP**s) by multi-hop communication; a sink moves around in the network and retrieves data from encountered RPs. **RPs are static**, data dissemination to RPs is equivalent to data dissemination to static sinks.

- Concerns: How to select the RPs.

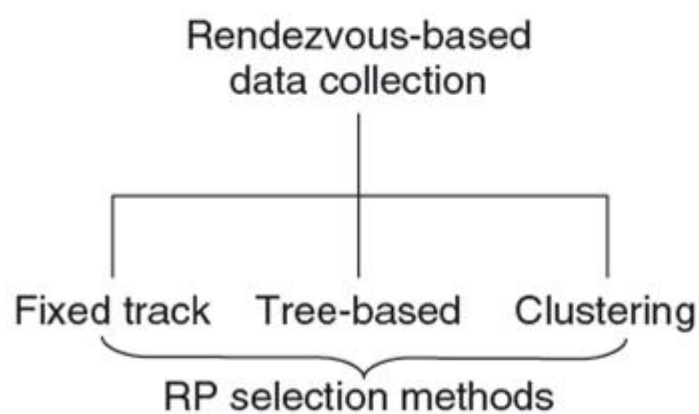


Figure 6. Data Gathering in delay-tolerant WSN – Rendezvous-Based data collection.

RP Selection Methods

- **Fixed Track:**

Kansal et al [8] proposed to use a straight-line sink path for data collection.

- There is a **single sink** in the network.
- Sink moves along a straight line and broadcasts a beacon while moving.
- A receiver node rebroadcasts the beacon if and only if the beacon comes along a shortest path it has seen.
- A number of minimum hop reporting trees are established along the sink path.
- This tree construction process takes place only once.
- The root of each reporting tree is a RP.
- Each sensor sends it measurements along an upward path to the root of its residing trees.
- When the sink arrives in its neighborhood, an RP sends its own data together with the data received from its tree members to the sink.

Xing et al. [9] considered the case that a sink moves along a fixed track of arbitrary shape.

- Data aggregation is applied at sensor nodes.
- Total energy consumption for message transmission along a multi-hop path is proportional to the Euclidean distance between sender and receiver.
- The objective is to select RPs along the sink track such that the total length of edges that connect sources to RPs is minimized.

RP Selection Methods

They presented a Minimum Spanning Tree (MST) based algorithm. In this algorithm.

RD-FT: an *optimal* set MSTs that connect all sources to the sink track (*sT*) in the Euclidean domain.

The set is optimal in that the total length sum of its member MSTs is minimal.

Each MST in the *set* satisfies the following two conditions:

- It is rooted either at the sink starting point, an end point, a turning point of, or at the projection point of a data source on *sT.*
- For any of its contained data sources, the length of the tree path to the root is smaller than the distance to any other point on *sT.*

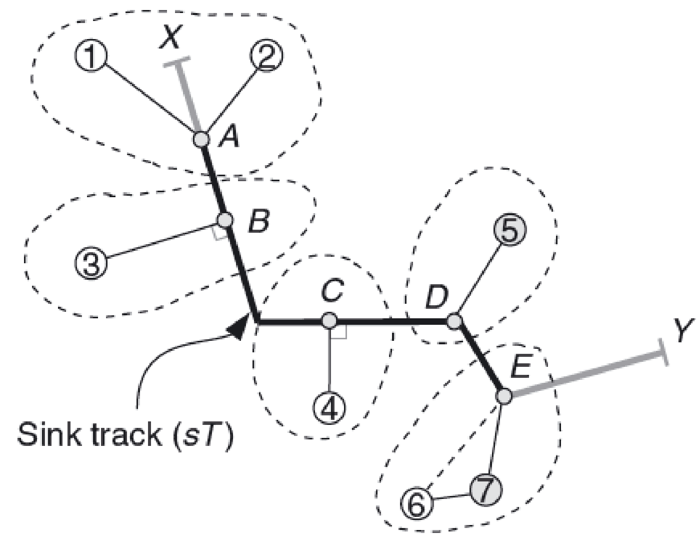


Figure 7. RD-FT

RP Selection Methods

- **Reporting Tree:**

Xing et al [9] studied RP selection along a geometric tree that approximates the reporting tree of data sources.

- RPs must be properly selected so that, the length of the sink tour is not larger than the maximum distance that the sink can travel within a given data collection **deadline**.
- Both constrained and unconstrained sink mobility are considered.

- A greedy algorithm was presented for sink mobility constrained on the tree.
  - Each tree edge is assigned a weight equal to the number of sources in the sub-tree rooted at its upper end (the end toward the root).
  - A sub-tree of total weight equal to half of the maximum travel distance is constructed by greedily selecting edges of maximum weight from the tree.
  - A partial tree edge may be selected at last to ensure exact total weight.
  - The sink tour is then determined by pre-order traversal of this sub-tree.

RP Selection Methods

In the case that the sink can move freely, they presented a greedy heuristic algorithm:

- This algorithm adds virtual nodes to the tree such that every tree edge is no longer than a **pre-defined value**.
- It iteratively selects as RPs the nodes with greatest utility (i.e. the nodes that will lead to greatest ratio of energy saving to length increase of the TSP tour of existing RPs).
- As new RPs are selected, already selected RPs whose utility becomes zero are removed.
- The selection process terminates when the maximum tour length is reached, or when all data sources are included.

RP Selection Methods

- **Clustering**

Rao and Biswas [11] presented a generic data collection framework *without location information*.

- In this framework, a minimum k-hop dominating set is constructed.
- Nodes in the dominating set are called *navigation agents* (**NA**).
- Two adjacent NAs are at least k + 1 and at most 2k + 1 hops away from each other.
- Each NA constructs a minimum hop tree rooted at itself and spanning up to a depth of 2k + 1 hops.
- During tree construction, it identifies adjacent NAs and meanwhile constructs shortest paths to them.
- The nodes along such a shortest path are called *intermediate navigators* (**IN**), they are used to navigate the sink to move between NAs.
- NAs and INs constitute a connected overlay graph.

RP Selection Methods

An existing distributed TSP algorithm is adopted to find a sink tour of NAs over the overlay graph.

- This algorithm enables each NA to know its next NA in the tour.
- The sink starts to move from an arbitrary location to discover a local NA by listening to a hello message.
- Once the first NA is discovered, sink moves toward the NA according to the received signal's Direction of Arrival (DOA).
- Afterwards, sink travels along the sink tour by following the DOA of signal of intermediate nodes.

The immediate neighbors of a NA, called *designated gateways* (**DG**), are RPs.

- Sources send data toward the sink tour using NA-rooted trees.
- Data stops at the closest DG on its way.
- Along its TSP tour, the sink retrieves data from encounters NAs and their DGs.

Conclusion

The algorithms described are almost centralized ones requiring full knowledge of the network. They do not scale well and have very limited applicability in practice, because WSN are usually deployed at random and full of dynamics (e.g. node failure and topological change).

In the rendezvous-based data collection approaches RPs are static, once selected they do not change. However due to message relay overhead, uneven energy depletion will appear around RPs as the network evolves, offsetting the effectiveness of the algorithm for network lifetime elongation.

Future research should address dynamic RP selection algorithms.

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