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Optimal Placement of Direct Cellular Link for Overhead Transmission Line Monitoring

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Abstract: Now a days, modernization of power grid plays a major role in reliable supply of electricity to meet the demand. The operating environment of power system is continuously monitored by sensors deployed in the transmission and distribution corridor. Information is periodically gathered through the sensors and transmitted to the control centre by relay node or master node of the transmission tower. Based on received information, control centre will take faster and smarter decisions. Traditional wired communications cannot meet the communication needs of online monitoring of transmission lines due to its complex nature. A combination of multiple wireless technologies (GPS, RFID, WLAN and cellular) with contemporary data analysis techniques is applied to reduce the complexity of data retrieval from transmission system. However, during the transmission of data, low data rate wireless devices cause bandwidth and latency bottleneck in Wireless Sensor Networks (WSNs). This problem can be reduced to certain level by optimally placing the direct cellular links in selected transmission towers. This study describes a novel shortest link path algorithm for optimal placement of direct cellular link respecting the delay and bandwidth constraints.

Key words: Delay, bandwidth, shortest link path, optimal placement, cellular link, overhead transmission line

INTRODUCTION

Power grid infrastructure is affected by so many threats such as natural disasters, human errors, power system component failures and communication system failures. The impact of equipment failures, capacity limitations, natural accidents and catastrophes cause power disturbances and outages in power system. In recent decades, the electric power industry has become more and more automated, interconnected and computerized. These modern methodologies have made improvement in online power system condition monitoring, diagnostics and protection. Due to the long distance between generation and consumption, extensive use of overhead transmission lines in the grid is required (Kiessling *et al*., 2003). Transmission tower provides structural support to the transmission line. For transmission line monitoring, sensors are put in various points of transmission tower and the information are gathered periodically by the control centre (Gungor *et al*., 2010; Ullo *et al*., 2010). The data acquired by these sensors are then transmitted along a network from one tower to another to the substation until it is collected in a central unit. Delivering this information to the control centre becomes a necessary issue to be solved for building an intelligent smart grid.

Control centre collects the information from the substation or directly from the transmission towers and sends the smarter system-level decisions and various control actions to remote towers or substations. To achieve high speed and low latency communication between substation and control centre, optical fiber communication is used as a backbone network (Gungor and Lambert, 2006; Ericsson, 2002, 2004). The interconnection between the transmission network and control centre is performed by various communication media such as wired, wireless and cellular technologies. Due to the bandwidth abundance, wired network like optical fiber may not be appropriate in the transmission lines in extremely large geographical area (Gungor and Lambert, 2006). The enormous data collection and transmission of collected data causes serious network congestion issues (Gungor *et al*., 2010). However, the congestion issues can be reduced by appropriately placing the direct cellular links on the selected transmission towers. Both WiMAX and 3G/4G cellular networks can provide wide-area data network coverage. The usage of direct cellular links may increase the capital and operation cost. This issue can be sorted out by optimal placement of cellular links in transmission towers which can provide effective data transmission respecting the bandwidth and delay constraints.

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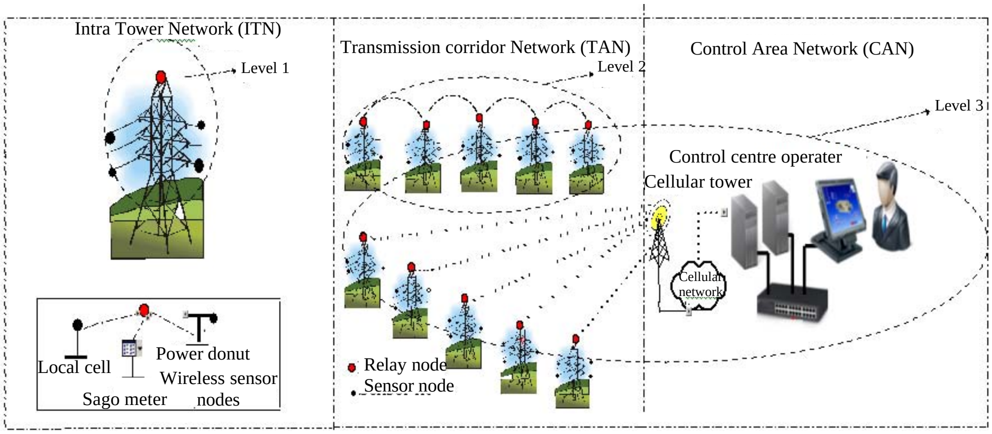

Fig. 1: Proposed communication network architecture of transmission corridor

In real time application, the transmission network is modeled as a linear network structure. The first proposed network models to support the overhead transmission line monitoring applications by Len *et al* . (2007), Chen *et al.* (2006) and Wu *et al.* (2012) presents a new reconfigurable network model of transmission line has been proposed where communication of sensor/relay nodes is through cellular network. In this regard, deploying cellular transceivers on every towezr will lead to more expensive communication. In order to reduce the capital and operating cost, enabling any one of the towers with cellular connectivity will provide high bandwidth, low latency and direct transmission to the control centre. This study focuses on proposing architecture for transmission line monitoring system for smart grid applications using WSN technology. In this study, a novel Shortest Link Path (SLP) algorithm is proposed for solving the direct cellular link routing optimization problem. Here, we need to make sure that the quantity of information sent over the network does not overwhelm the system, the link capacity is worth such that no link has a flow under a permissible range; the delay over the network is reduced; higher bandwidth is provided.

Proposed network model: This study proposes the communication network architectures for smart-transmission grid. The power transmission set up is roughly divided into three domains in terms of communication coverage and functionality, namely intra transmission tower network, the transmission corridor network and the control area network. These network domains can be implemented using hybrid mode of communication technologies such as wire-based and wireless-based solutions. In view of wired solution, fiber optic based communication is suitable for control area network. IEEE 802.15.4/(ZigBee) would be more suitable for transmission corridor network. Bluetooth and ZigBee would be suitable for intra transmission tower network.

Hierarchical network architecture: The proposed network architecture for the smart-transmission grid communication consists of three levels; the Intra Tower Network (ITN), the Transmission Corridor Network (TCN) and the Control Area Network (CAN). Figure 1 depicts the proposed network architecture. In this research, the three level hybrid hierarchical network model by Fateh *et al.* (2013) is followed in which a transmission corridor comprises number of transmission towers, two Substations (SS1, SS2) and a Control Centre (CC) where Level 1 is an internal sensor network of a single transmission tower. The sensor nodes in the ITN are equipped with wireless transceivers. Level 2 is the TCN and it performs tower-to-tower interaction in the infrastructure. Level 3 is the CAN to collect and transmit the information from the transmission tower to control centre. To facilitate the hierarchical network architectures, a hybrid communication such as combination of fiber optic (wired) and ZigBee cellular (wireless) is employed throughout the network. The use of sensor networks has been proposed for applications like mechanical state processing and dynamic transmission line rating applications (Malhara and Vittal, 2010). The mechanical failures such as conductor failure, tower collapses, hot spots, extreme mechanical conditions are monitored and the data are transmitted using wireless sensor nodes (Yang *et al.*, 2006, 2007) having minimum processing capacity and short transmission communication used for online power system condition monitoring, diagnostic and protection. In this respect, the intelligent monitoring and control enabled by online sensing technologies have become essential to maintain safety, reliability and uptime of the smart grid (Lu and Gungor, 2009; Gungor and Hancke , 2009; Akyildiz *et al*., 2002; Culler *et al*., 2004; Lewis, 2004). Each tower is equipped with a group of sensors in a form of cluster. Each cluster is equipped with a master node or relay node. The node with long transmission range is habituated as a master node and the collected data are transmitted to the substation or to the control centre. Here, Level 1 communication, showed as cluster, occurs between the wireless sensor nodes and master node. Sensor nodes send their data's to the master node in this pace. The master node continuously monitors data from all wireless sensor nodes belonging to its cluster. Level 2 communication occurs among master nodes of adjacent towers. Due to long geographical area of the transmission towers, multi-hop approach is utilized to transmit data. In case, the master node is not directly connected to the substation, then it would send its information to the substation in a hop to hop manner through its neighboring towers. Level 3 communication is between a master node and control centre or substation and control centre. In smart grid environment, the status of transmission line monitoring is updated periodically. So, the data should be collected within the specified delay and within the allowable bandwidth.

Problem formulation: The transmission tower environment employs a linear network and different paths may be considered for transmitting data from a source node to the control centre by considering the bandwidth limit of the link and the maximum allowable delay for the network. A path may be linked with more than one performance metrics (e.g., each path has a fixed delay and a capacity). Based on the quality, path may be sorted and the data can be routed through multiple paths to the control centre. However, we may get inconsistent orderings if the paths are sorted according to different performance metrics. For example, a path may have a higher bandwidth but a higher delay while another path may have a smaller bandwidth but a lower delay. Such inconsistency makes it very difficult to decide which path to use. Hence, an approach is required to find a feasible combination of paths.

This study focuses on the optimal path selection based on the performance metrics of bandwidth and delay. The problem is to find a path to route the data between the source and destination with minimum end to end delay and allowable bandwidth limit. The objective is to find a set of flow values within the allowable bandwidth of each link such that the mean delay over the network will be low. Here, the transmission line is modeled as a directed graph:

$$G = (V, E)$$

Where:

V = The finite set of vertices (network nodes including the control centre)

E = The set of edges (network links) representing the topology in terms of communication links that can be wired or wireless

The substations can be modeled as a single sink node. There are N master nodes between the two substations. These nodes are labeled as node 1 and 2, ..., node N where, node 1 and N are directly connected to a substation. Node 1 to node N is distributed in a linear structure. In the linear network model (Len *et al.,* 2007; Chen *et al.*, 2006) if a master node is not directly connected with the substation then it would send information to the substation through the neighbour master nodes in a hop to hop manner. Two non-negative real value functions are associated with each link, i.e., delay and available bandwidth. Each link (i, j) is associated with capacity constraint $B_{i,j}$ and delay constraint.

Given the network as described in the objective of this formulation is to minimize the number of cellular transceivers such that the tower node can communicate with the control centre in an efficient manner. Equation 1 is given:

$$\text{Minimize } Y = \sum_{i \in N} Y_i \tag{1}$$

Equation 1 is the objective function for the formulation that minimizes the total number of cellular transceivers required to be deployed in the path.

Subject to the constraints: In practice, network experiences large packet loss and bad performance due to unlimited bandwidth. Shared wireless channels are committed to bandwidth-limitation. Hence, bandwidth is considered as a limiting factor. This research specifies the nominal amount of data that can be transmitted by a wireless link in the network as a constraint. Using link capacity, the following equations formulate bandwidth limitations. The total flow on each link must not exceed the available link bandwidth which can be expressed as:

$$\sum_{k \in N} B_k X_{i,j,k} \leq B_{i,j} \quad \forall (i, j) \in E \tag{2}$$

The end to end latency of every flow must be less than or equal to the maximum permissible end to end deadline which can be expressed as:

$$\sum_{(i,\ j)\in N} D_{i,\ j,\ k} X_{i,\ j,\ k} \leq D \forall k \in E \qquad (3)$$

Equation 4 ensures that each flow must be less than or equal to the capacity of the edge. The capacity rule should not be violated and has to be confined within the specific up and down bounds as:

$$0 \leq X_{i,\ j} \leq B_{i,\ j} \qquad (4)$$

Where:

$B_{i,\ j}$ = The available link specific bandwidth, capacity or upper bound on the arc (i, j)
D = The end to end deadline
$D_{i,\ j,k}$ = The latency incurred by the kth flow on the link (i, j)
B_k = The flow bandwidth necessity for node k
Y_i = Cellular transceiver location at node i
N = The number of towers/nodes in the transmission network
$X_{i,\ j,\ k}$ = The binary variable and defined as follows: if arc (i, j) is traversed by the flow from node k, then $X_{i,\ j,\ k} = 1$; $X_{i,\ j,\ k} = 0$ otherwise
$X_{i,\ j}$ = Takes values 0 or 1, to show whether or not the link (i, j) is used to carry information to the control centre

Optimal location of direct cellular link: Each master node of transmission tower has to transmit its information to the control centre. Here, it is assumed that, the size of the packet data transmitted from each master node is of same length. The data flow can take any path to reach the control centre, i.e., through wireless and fiber optics media, wireless and cellular communication or directly cellular media. The entire tower shares the same wireless channel, i.e., IEEE 802.15.4 standard (IEEE 802.15.4 Standard, Oct. 2003)/ZigBee technology of data rate 250 kB. Packets are allowed to transmit from one tower to another tower based on the residual bandwidth available on that link. If the available bandwidth is greater than the required bandwidth, then the link allows the flow. If the flow in a link exceeds the capacity of the link, then congestion occurs, even though the data packet size is assumed to be uniform. When the flow bandwidth exceeds the link capacity, i.e., 250 kB, then the only option is deploying a direct cellular link or to use fiber optic cable in the transmission corridor. Within the limited capacity of wireless IEEE 802.15.4 standard ZigBee links, the information delivery might not be able to meet the latency constraints. When the deadline requirement is very stringent, a direct cellular link should be installed in each tower which ensures huge cost. For relaxed deadline requirements the lowest cost is attained by fully utilizing the wireless network.

Table 1: Delay and bandwidth structures of various communication media

Media	Type of the link in the network	Max. data rate	Max. coverage	Delay
Optical fiber	Substation to control centre	10 (GB)	As long as fiber	≈1 μsec
Wireless (ZiGbee/ 802.15.4)	Between towers and substation	250 (kB)	10 m-1.5 km	≈10 m sec
Cellular	Transmission towers to cellular tower	100 (MB)	100 m -10 km	≈50 m sec

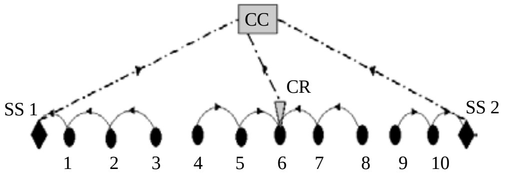

Fig. 2: Selection of optimal path

Installation of more direct cellular links is very expensive which incurs high installation costs. So, only way of addressing this problem is to find the optimal location of direct cellular links which minimizes the end to end delay and would meet the bandwidth constraint. Table 1 summarizes the delay and bandwidth of various communication media used in this study.

Figure 2 depicts how the information is effectively delivered from each tower to the control centre. Data from the towers nearer the substation, i.e., tower 1-3 take the route to the control centre through the substation SS1 where as the data from the tower at the centre of the transmission corridor, i.e., tower 4 and 5 use the direct cellular link (CR) installed at tower number 6 to reach the control centre. Tower 6 uses the cellular link directly for its transmission. Tower 7 and 8 uses the cellular link at tower 6 to reach the control centre. Tower 9 and 10 choose the cost effective path via. substation SS2 to the control centre. Based on minimum end to end delay and allowable bandwidth limit, optimal path is selected for each tower.

MATERIALS AND METHODS

The solution of the direct cellular link placement problem is to find a feasible path between each tower and control centre by considering the bandwidth limit of the link and the maximum allowable delay for the network through MATLAB simulation. The proposed novel Shortest Link Path (SLP) algorithm is described by means of the flow chart in Fig. 3. In the proposed approach, all the possible paths for a packet from each tower to the control centre is analyzed and evaluated whether they are within the limit of constraints (end to end delay and bandwidth). Based on the evaluation, a packet is sent

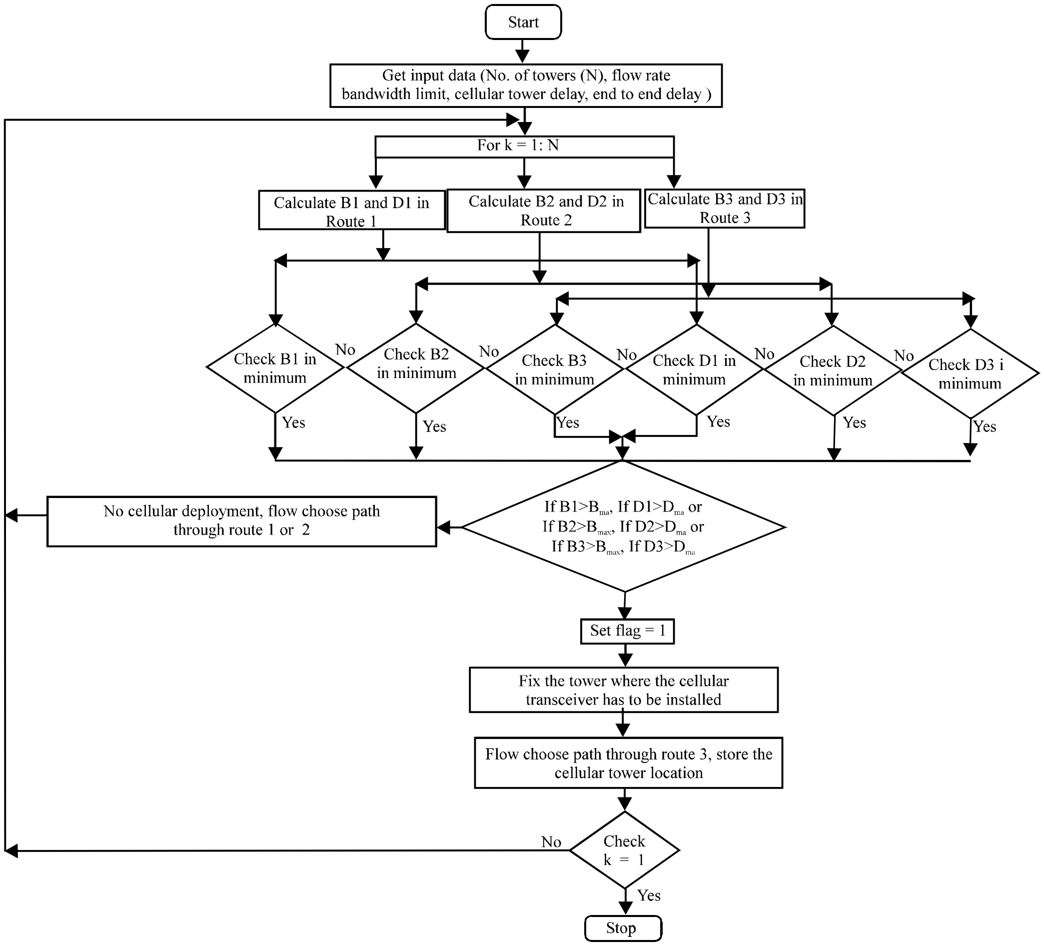

Fig. 3: Flowchart for the SLP algorithm

through a path with minimum delay and allowable Bandwidth (B(p) and D(p)). Then SLP algorithm checks whether the selected path bandwidth is within the permissible limit of maximum bandwidth of the link. If, it exceeds the maximum bandwidth limit, congestion of packet occurs resulting in delay in the delivery of packets and it may cause loss of packets. Hence, path diversity is required at this stage to avoid packet loss and to reduce the delay in delivering the packet. So, the direct cellular link is installed in the congestion.

Traffic area in the nearby tower where it can route the packet to the control centre within a reduced delay and allowable bandwidth. The SLP algorithm devises a mechanism to find the number and location of direct cellular link in the tower. Once the cellular enabled tower is deployed in the transmission corridor in order to meet the bandwidth requirements of the flow and to reduce the delay in packet delivery, all the packets from the centre transmission towers may follow the cellular link enabled tower to reach the control centre.

Each link (i, j) in the path is assigned a real number $B_{i,\ j}$, $D_{i,j}$. When the link (i, j) is inexistent, $B_{i,j} = 0$; Let, $B(p) = \min (B_1, B_2, B_3)$. Let $D(p) = \min (D_1, D_2, D_3)$ where $D_1 = D_1+SS1+CC$ is the delay taken by the packet to travel from a tower node in backward direction through the substation to the control centre through the common wireless medium (ZigBee) $D_2 = D_{1,2}+D_{2,3}+D_{3,4}, \ldots,+D_{N-1,N}+SS2+CC$ is the delay taken by the packet to travel from the same tower node in forward direction to the control centre via. substation through the common wireless medium (ZigBee) and $D_3 = D_{1,\ 2}+D_{2,\ 3}+D_{3,\ 4}+D_{CR}+CC$ is the delay incurred by a packet to travel from the same tower node through the direct cellular link to the control centre. Similarly, B_1-B_3 are calculated where B_1 is the bandwidth of the packet to travel from a tower node through the substation to the control centre through the common wireless medium (ZigBee), B_2 is the bandwidth of the packet to travel from the same tower node in forward direction to the control centre via. substation through the common

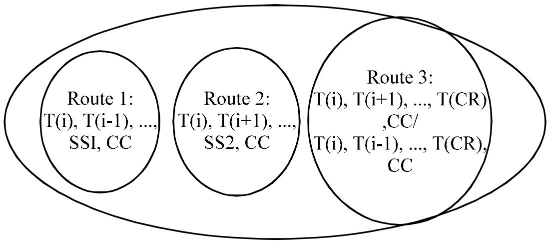

Fig. 4: Route representation for each tower to the control centre

wireless medium (ZigBee) and B_3 is the bandwidth incurred by a packet to travel from the same tower node through the direct cellular link to the control centre. The entire possible path for all the tower nodes to the control centre is found out and the corresponding delay and bandwidth are evaluated.

The path with minimum delay and bandwidth is selected as best path. Based on the evaluation, a path will be chosen with minimum delay and allowable Bandwidth (B(p) and D(p)) for transmission of packets. Then the selected path bandwidth and delay are subject to maximum allowable bandwidth constraint and end to end delay constraint checking. When it exceeds the maximum bandwidth of the wireless link (250 kB) and the end to end delay limit, packet transmission through wireless link alone is insufficient. So, direct cellular link is installed in the congestion traffic area in the corresponding tower node where it can route the data to the control centre within a permissible delay and bandwidth. Figure 4 shows the route representation of each transmission tower. In the proposed research, each node can take three routes such as route 1-3. Route 1 denotes the path of a flow from a tower in backward direction to the control centre, route 2 denotes the path of a flow from a tower in forward direction to the control centre and route 3 denotes the pathway of flow from a tower directly to the control centre through cellular link. Here, T indicates the tower location and CR indicates the cellular transceiver.

RESULTS AND DISCUSSION

Performance evaluation: In this study, 20 towers with an average span length of 800 ft (www.atcllc.com) are considered as a transmission line network test system. The bandwidth of IEEE 802.15.4 wireless links is 250 kB, bandwidth of cellular links is taken as 75 MB and the bandwidth of optical fiber links is taken as 10 GB. The end to end deadline of the network is taken as 56, 64, 80, 96 and 112 msec. The packet size generated by each tower is same. The tower to tower latency is considered as 8 msec. Simulation for 20 tower test system was developed using MATLAB platform. In this simulation, the data rate of the packet transmitted by each tower is taken as 32 kB. With the above said inputs, the 20 tower test system is simulated using the proposed SLP algorithm and the results are tabulated in Table 2. Table 2 gives a clear idea about the Cellular Transceiver Locations (CTL) for various delay constraints. It clearly indicates that if the end to end delay requirement is less, then the deployment of cellular transceiver is increased and vice-versa. Here, ‘1’ represents the placement of cellular transceiver locations in the transmission towers.

Table 2: Deployment of cellular transceiver for various delay constraints

	End to end delay				
CTL	56 (msec)	64 (msec)	80 (msec)	96 (msec)	112 (msec)
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	1	1	1	0	0
9	1	0	0	1	1
10	1	1	0	0	0
11	1	0	0	0	0
12	1	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0

Effect of end to end delay in deployment of cellular tower: Simulations were carried out for 20 node network test system with a constant flow bandwidth of 32 kB. The results show that for stringent deadline requirements of 56 m sec, 5 cellular transceivers have to be deployed in the transmission corridor which incurs a huge cost. To meet the delay and bandwidth constraints, node 1-5 rely only on wireless/ZigBee links for routing the packet to the control centre whereas node 6, 7, 13, 14, 15 use both wireless link and cellular link to route the packet to the control centre. Node 8-12 utilize purely cellular link to meet the delay constraint which increases the installation cost of the network. Data transmission from node 16-20 relies only on wireless links which ensures a cost effective transmission. For the deadline requirement of 64 msec, 2 cellular transceivers have to be deployed in the corridor which reduces the cost compared to the previous one. To meet the delay and bandwidth constraints in a cost effective manner, node 1-4 utilize wireless/zigbee links for routing the packet to the control centre but node 5-7 use

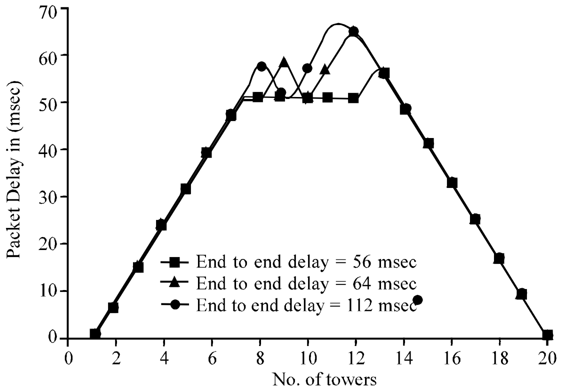

Fig. 5: Effect of variation in end to end delay

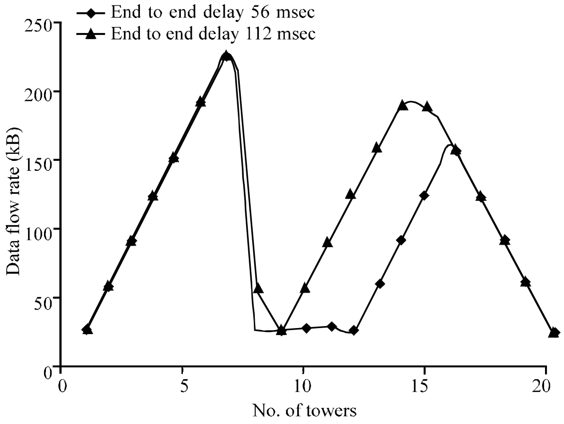

Fig. 6: Effect of variation in flow bandwidth

both wireless and the cellular link installed in tower 8 for its transmission. Packets from tower 8 reach the control centre faster by using direct cellular link deployed in it for transmission; packets from tower 9 make use of either the cellular facility in tower 8 or tower 10. Packets routed from tower 11-15 follow the wireless link as well as the cellular link in node 10 to meet the delay and bandwidth constraints. Packets routed from tower 16-20 follow pure wireless link. For the case of deadline requirement of 112 msec, only one direct cellular transceiver is deployed at the transmission corridor. Figure 4 shows the effect of end to end delay in deployment of direct cellular link in the transmission tower. When the delay requirement is increased further, packet transmission may rely on wireless network in short transmission area. Full utilization of wireless network causes packet loss in-between hoping process. To get a feasible and cost effective solution, deadline requirements play a vital role in optimal selection of cellular link placement shown in Fig. 5

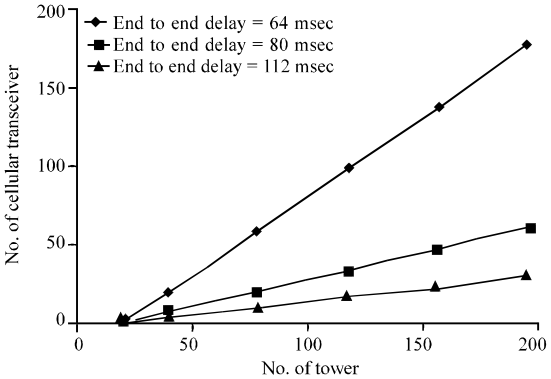

Fig. 7: Deployment of cellular transceiver for various size of network

Effect of flow bandwidth in deployment of cellular tower: Figure 6 shows the of the entire network for various end to end delays. This figure clearly shows that, for a 20 node test system with flow bandwidth of 32 kB and end to end delay of 56 msec, 5 cellular transceivers have to be deployed in the corridor. For tower 1-5, the flow bandwidth requirement is less than the available bandwidth, hence, packet routing relies only on wireless/ZigBee links which is cost effective. Because of the constraints such as limited bandwidth and latency, the towers 6-15 use both cellular and wireless links for packet delivery to the control centre. Cellular link usage makes the system more expensive than wireless, so, tower 16-20 uses the wireless link instead of cellular link for data routing. In the case of the end to end delay requirement of 112 msec, this delay does not affect the bandwidth flow up to available bandwidth of the link and the packet routing depends on wireless/ZigBee link. When it exceeds the bandwidth limit, the algorithm chooses the direct cellular link as its path for data transmission. Here, only one cellular link is needed to satisfy the flow rate and end to end delay. The performance graph echoes this observation.

Effect of network size: Figure 7 reveals the effect of variation in the deployment of cellular transceivers with respect to the number of transmission towers. We experimented this for the end to end delay of 64, 80 and 112 msec with a constant flow bandwidth of 32 kB for the network size ranging from 10-200 nodes. The figure clearly shows that the cellular transceiver increases linearly with respect to the number of transmission towers in a linear network.

CONCLUSION

A novel Shortest Link Path (SLP) algorithm is proposed for solving the direct cellular link placement problem. This approach provides desired level of quality of service by reducing the network latency with respect to the bandwidth requirement. A detailed performance analysis is carried out for the optimal placement of cellular link with various end to end delay constraints. By studying the trade-off between bandwidth and delay performance, the proposed novel SLP algorithm succeeds to find out the optimal location of direct cellular link for the test system being considered. After a detailed analysis of the simulation results, it is found that for a lower end to end delay the number of cellular links will increase and vice-versa. Increasing number of cellular links will make the system as a costlier one. The obtained solution with direct cellular link is shown to be significant and the proposed approach is very effective method for the solution of cellular link placement problem.

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