Cost Optimal Hybrid Communication Model for Smart Distribution Grid

Aryadevi Remanidevi Devidas and Maneesha Vinodini Ramesh

Abstract—**There have been significant changes and dynamic growth in power grids since the inception of the smart grid. To ensure a self-sustainable grid, the power grid should facilitate the real-time sharing of the dynamic attributes of the power grid between the spatially distributed power grid elements. This demands a flawless design of the overlay communication network for a smart grid. However, instrumenting the entire grid with intelligent communication devices would be prohibitively expensive. A cost-optimal model is necessary to select the actual cardinality of intelligent communication devices required for the data transmission by ensuring its Quality of Service (QoS) metrics. This research work presents a smart distribution grid architecture with a network of microgrids and details the need for hybrid communication for intra-microgrid communication. A cost-optimal model is proposed to offer an optimal combination of technologies for intelligent devices in the hybrid communication overlay network. The formulation considers QoS metrics such as data packet latency, bandwidth requirement, link reliability, packet drops, and communication range of the technology to derive a cost-optimal solution. Based on this model, a Recursive Algorithm for Cost Optimal Combination of Communication Technology (RACOCCT) for a power grid topology is presented in this work. The simulation study performed on selected power grid topology based on the Standard IEEE 33 bus network reveals the cost-optimal combination of hybrid wireless communication technologies for the varying probability of link unreliability.**

Index Terms—**Smart distribution grid, hybrid communication network, network planning, microgrid, quality of service metrics, cost optimization.**

I. Introduction

Advancements in the electricity sector and the increased scope of utility companies are vital for the sustainable development of any modern community. The urge to mold our lives to be more comfortable prompts us to use electric devices in every aspect of our life [1]. More or less, this desire for comfort encourages a change in the traditional power grid. This thrust and the advances in Information and Communication Technology was the impetus to transform the legacy power grid into a smart grid. Smart grid integrates sensing, processing, communication, and control facilities to almost all grid entities to make them smart. The intelligence lies in the proper delivery of sensed information from the source entity to the destination entity to accomplish the correct decision instantaneously at the appropriate time. This process indicates the need for proper design and formation of the overlay communication network for the power grid.

Wireless communication technologies offer remote control and monitoring of the power grid without incurring the additional cabling cost of wired communication technologies [2], [3]. Provisioning reliable communication in a vast power grid is tedious [4]. Various wireless communication technologies, including Cellular, Wi-Max, Wi-Fi, LTE, ZigBee, and Bluetooth, can be used for smart grid communications [5], [6]. Park and Son have proved that a hybrid communication scheme for smart grid applications is cheaper than a single scheme using an economical cost model based on a real-time implementation of smart metering infrastructure [7]. Therefore, choosing the appropriate communication technologies that concurrently offer reliability, security, and the required levels of Quality of Service (QoS) metrics such as bandwidth, latency, and packet losses is a significant challenge in designing the communication architecture for a smart distribution grid [8]. Controlling the information flow of a distribution grid is also challenging due to the inherent scale of the grid. This could be managed by operating the existing grid distribution grid as a network of microgrids.

A smart distribution grid with distributed microgrid architecture depends on a tight linkage between the cyber and physical layers. Hence, the ICT systems are the core elements of microgrids [9]. A smart distribution grid with intelligent two-way data communication can generate a significant amount of data that needs to be transferred and processed for wise decision-making. The solution is to position intelligent communication devices throughout the grid depending on the different functionalities desired. However, instrumenting the entire smart distribution grid with these intelligent devices is prohibitively expensive. Thus, a cost-optimal model is necessary to select the exact quantity of intelligent devices required for the data transmission with the required QoS metrics [10].

In this work, we portray an overview of intelligent distribution architecture with a network of microgrids from our previous work and present the need for hybrid communication for intra-microgrid communication. We then formulate an optimization model which gives a cost-optimal combination of technologies for intelligent devices for the hybrid communication overlay network. The formulation considers the QoS metrics such as data packet latency, bandwidth requirement,

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link reliability, packet drops, and the communication range of the technology for the derivation of the cost-optimal solution. The proposed algorithm RACOCCT recursively finds the cost-optimal communication technology combinations for a power grid topology. The simulation study shows the cost-optimal combinations of technologies for the varying probability of link unreliability using the communication technologies such as ZigBee, Wi-Fi, and Cellular.

The rest of the paper is organized as follows: Section II discusses the related work, and Section III describes our contributions. Section IV describes the architecture of a smart distribution grid with a communication overlay network. Section V describes the requirement of a hybrid communication architecture for a smart distribution grid. Section VI presents the problem description, the cost-optimal hybrid communication model, and the algorithm RACOCCT. Section VII gives the simulation results and related discussions. Finally, Section VIII concludes the paper.

II. Related Works

This section presents recent and relevant research on communication networks for smart grids, focusing on various communication network architectures, network planning, and different optimization techniques for communication networks of smart grids.

Ali and Hussain discussed Optimal Power Flow (OPF) models and the modelling of microgrid services and their mapping to communication protocols. But they have not studied the cost-effectiveness of the communication architecture design [11]. Moghimi *et al.* proposed a two-level hierarchical communication platform for multi-microgrid energy management that considered only the inter-microgrid operations and not the intra-microgrid functionalities [12]. Deng *et al.* scrutinized a secure communication architecture for smart grids [13]. They also detailed a secure protocol titled the Attribute-based Cryptosystem. The message is designed to be read by a group of users that satisfy specific access control rules and secure communication in the smart grid. However, the communication architecture only deals with data transfers from the consumers and the utility. The authors failed to consider any other data transfers in smart grids. Therefore, the architecture proposed in their paper does not serve the primary functional requirements of a smart grid. Zografopoulos *et al.* discussed security and interoperability challenges in the implementation and deployment of smart grids [14].

Xu *et al.* presented a comprehensive study on the access networks for Automatic Metering Infrastructure (AMI) applications in a smart grid. To achieve the reliability goals, they resorted to multiple redundant links [15]. Their study clearly shows that link reliability is inversely proportional to the number of redundant links. Nonetheless, the increase in redundant links increases the overall cost of the system, and the paper presented unsustainable explanations on cost-minimization. Erol-Kantarci and Mouftah presented a survey of information and communication infrastructures for smart grids, including a Smart Grid-Wide Area Network (SG-WAN), a Smart Grid-Neighborhood Area Network (SG-NAN), and a Smart Grid-Home Area Network (SG-NAN) [16]. However, the survey does not indicate the design of a smart grid functionality-based communication network. Saleem *et al.* presented an Internet of Things (IoT) based smart energy management system which incorporates various communication interfaces and protocols to integrate with any software-based smart solution [17]. They have provided the system architecture, design, and integration of IoT-enabled smart meters, including an IoT middleware module.

Qi *et al.* presented an optimal planning method for a smart grid communication network considering the network construction cost and communication latency [18]. However, the reliability factors associated with the communication network are not considered for optimal planning. In the research paper [19], Zhu *et al.* explained the cost and optimal placement models for communication links for Phasor Measurement Units (PMU). The fact that wireless communication is exposed to link unreliability must be taken into account while designing the communication cost model. In the research paper [20], the author has introduced an analytical network-planning framework that estimates the coverage area of the wireless communication architecture for a smart distribution grid. However, the cost analysis is not explained. Huang and Wang studied the minimal cost planning problem of access points in the neighbourhood area network (NAN) of the smart grid communication system [21]. They have considered two wired technologies optical fibre and power line communication for the study, but wireless technologies offer significant benefits over wired technologies for smart grid communication [22]. Chang *et al.* described a distributed neuro-dynamic optimization method for energy management in a smart grid that minimizes operational cost [23]. However, it has not considered the Installation cost, the communication cost, and the maintenance cost of a smart grid. Lang *et al.* formulated a mixed-integer optimization model for data aggregation point placement for smart meters in a smart grid. They included the installation cost, the transmission cost, and the delay cost [24]. However, they did not take the link unreliabilities in the model into account.

Gallardo *et al.* presented network planning for advanced metering infrastructure where they have proposed a clustering algorithm-based technique for the placement of data aggregation points [25]. However, the authors did not discuss the overall cost-effectiveness of the communication network for advanced metering infrastructure. In the research paper [26], the authors show the application of a Time Sensitive Networking system, which is a viable option for substation environment communication flows. This work can be extended further to the grid after studying the reliability studies of the network. Peng *et al.* presented a discrete-time self-triggered distributed controller for load sharing and voltage regulation in DC microgrids [27]. They have further proposed an algorithm to reduce the effects of data dropouts and communication delays for the effective working of the controller. Ye and Bose discussed the communication protocol stack and clustering optimization of different topologies for PMU based applications [28]. Almasabi and Mitra discussed the strategy of deploying PMUs and considered both installation cost and the extent of system observability in the presence of network vulnerabilities [29]. Nonetheless, they have not analysed the cost and reliability factors of the communication topologies. In the research paper [30], the author developed a model to determine the communication route failure probability for interdependent power grids. The optimization model finds the best route that reduces the impact of the initial route failure. The message complexity of the best route discovery algorithm and the analysis of its cost effectiveness was not addressed.

Based on the literature review presented above, as far as we know, there is no existing work that has proposed to deal with the problem of the optimal combination of technologies for intelligent intermediate devices for the hybrid communication overlay network of a smart distribution grid. This is a strong indication of the novelty of this work. In this paper, we have extended our previous research work [31] in order to determine the optimal combination of intermediate devices with multiple communication technologies supporting a hybrid communication architecture for a smart distribution grid. This paper has also proposed a novel algorithm, RACOCCT, to scale up the cost optimal method to a power grid topology. The simulation experiments and its results, presented in this paper, demonstrate the optimal intermediate device combinations with respect to the variations of the overall cost of the communication network, the variations in the probabilities of link unreliability, source to destination distances, increased prices for Wi-Fi and Cellular and so on.

III. Our Contributions

Our cost-optimal model is generic and considers the QoS metrics requirements of the data packet from source to destination. However, for the simulation study we have considered the data packet CDP (Consumer Data Packet) generated from the SCNs (Smart Consumer Nodes) to the MCSs (Microgrid Control Stations).

Contributions of this paper are summarized as follows:

1) A hybrid communication architecture for a smart distribution grid, comprising of several microgrid patches.
2) A cost-optimal model for the hybrid communication network of a smart distribution grid, considering the QoS requirements of data flow between different entities.
3) Recursive Algorithm for Cost Optimal Combination of Communication Technology (RACOCCT) to determine the cost-optimal combination of intermediate devices for a power grid topology.
4) Comprehensive analysis of the combination of intermediate devices with different parameter settings (including the variations in probabilities of link unreliability, individual cost variations of devices with different technologies, variations in the source to destination distance and so on) on the optimal cost of the hybrid communication network. Numerical experiments verify that the proposed cost-optimal model can be solved efficiently.
5) Scalability validation of the RACOCCT algorithm on IEEE 33-bus test system.

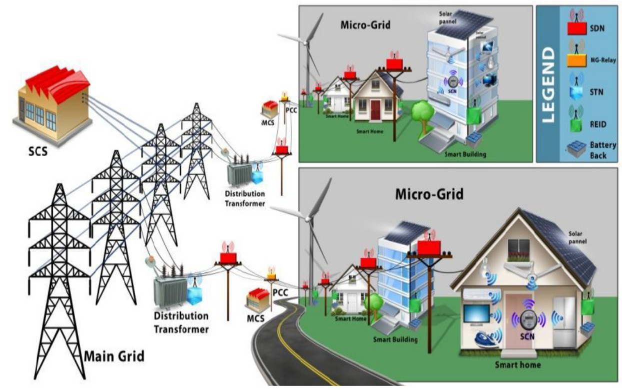

Fig. 1. Architecture Diagram for Smart Distribution Grid.

IV. Architecture Overview

In this section we present an overview of the smart distribution grid architecture as a network of microgrids from our previous work [31]. In order to facilitate conformance to the functional requirements of the microgrid, intelligent devices such as Smart Consumer Nodes (SCN), Smart Distribution Nodes (SDN), Renewable Energy Intelligent Devices (REID), Smart Transformer Nodes (STN), Microgrid relays (MG-Relays), and a Microgrid Controlling Station (MCS) are integrated with the power grids as shown in Figure 1.

Basically, all set of nodes presented in the smart distribution architecture are furnished with a sensing and actuator module, a computing module, and a communication module. It gives flexibility to the designer to choose between two options:

1) Design of a generic intelligent device that includes all features of all intelligent devices
2) Design a unique intelligent device that fulfils specific functional requirements.

To achieve all the functional requirements, numerous intelligent devices need to be deployed in proper locations within the grid. If the number of devices is reduced, the overall performance and some of the microgrid functionalities are diminished. Designers have the freedom to choose from different options based on the performance requirement and the cost of the system. The performance versus cost trade-off analysis determines the number of intelligent devices in the smart distribution architecture.

Powering of the intelligent devices and their energy consumption is a matter to investigate. The energy drawn by the microgrid communication and controller infrastructure is affected by the specifications of the module chosen for the design of the intelligent devices. For example, if Raspberry Pi is used, then the power consumption varies from $0.2W$ to $1.2W$ based on the selected Pi model. If the module operates for $1hr$, the energy consumption varies from $0.2Wh$ to $1.2Wh$. Renewable energy sources, batteries, or the grid itself can power the intelligent devices [32]. Selection of either a renewable energy source or batteries for powering the grid will increase the cost of the microgrid communication infrastructure, as the cost of the powering technologies chosen for the intelligent devices adds to the entire infrastructure cost. In this work we are assuming that the intelligent devices are powered

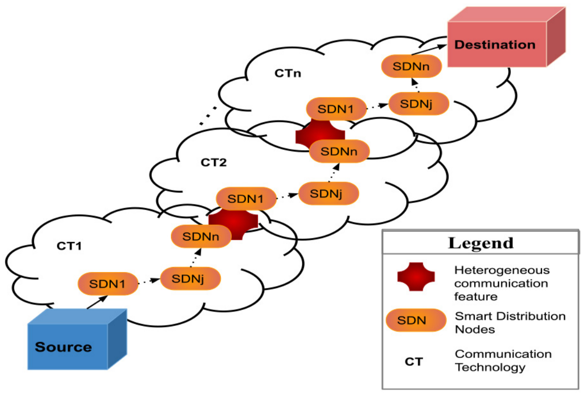

Fig. 2. Network diagram showcasing the hybrid communication inside a microgrid of smart distribution grid.

from the grid itself. Wisely selecting the number of cost-optimal intelligent devices will diminish the overall energy consumption of the communication infrastructure to a great extent. The selection must be balanced without compromising the required values of data communication attributes.

V. Need of Hybrid Communication Architecture for Smart Distribution Grid

One of the foremost goals of the overlay communication network for smart distribution grid architecture shown in Figure 1 was to ensure reliable and real-time communication of information about different entities in the distribution grid. This goal is necessary for the smooth working of each microgrid and the real-time decision-making in the smart distribution grid. Because the grid entities are spatially distributed and highly location-dependant, the overlay communication infrastructure causes communication link unreliability. For that reason, single communication technology alone will not be adequate to deliver data packets with varying Quality of Service (QoS) requirements from diverse power grid entities. A combination of optimal communication technologies ensures reliability in the communication architecture of the smart distribution grid.

Most of the present research works [33]–[35], in this area are recommending a heterogeneous communication architecture with different communication technologies and their seamless integration. In heterogeneous communication architecture, the communication devices are capable of communicating with each other irrespective of the technologies employed in each of the devices. Technologies include: ZigBee, Wi-Fi, Cellular, Wi-Max, Power Line Communication (PLC) and so on. Incorporation of a heterogeneous communication feature in all the devices results in the surge of overall cost of the communication network. Less expensive is the hybrid communication architecture for a smart distribution grid, wherein the heterogeneous communication feature is required only in places where a technology change happens in the network of intelligent devices as shown in Figure 2.

A hybrid communication architecture is more suitable for the smart distribution grid for the following reasons:

1) The smart distribution grid should be alive in all environmental conditions. In extreme environmental conditions, a single technology deployed may or may not work. If there are a variety of technologies, the chance of successful data delivery is higher.
2) The use of a heterogeneous communication feature in a limited number of intelligent devices where there is a technology transition will cut down the total cost of the communication network for a smart distribution grid.

VI. Cost Optimal Model

A. Problem Description

The data packets generated from the SCNs is termed as a Consumer Data Packet (CDP). Based on the network diagram shown in Figure 2, the SCNs are the source and the MCS is the destination.

As we discussed in the previous section, the hybrid communication model selects the most appropriate combination of communication technologies to deliver data packets from the source to the destination. For instance, within a microgrid of the smart distribution grid, the SCNs of each smart building transmit data packets regarding the energy consumption to the MCS.

Real-time monitoring of energy consumption is just one of the microgrid functionalities. Other functionalities include power theft detection and line fault detection which are achieved through SDNs. These SDNs can act as intermediate nodes to relay the data packets from the SCNs. Because the power grid on the distribution side is radial, the communication network will also follow radial topology to accomplish all the microgrid functional requirements. If we have communication technologies $CT_1, CT_2, \ldots, CT_n$ and a set of SDNs (intermediate nodes $SDN_1, SDN_2, \ldots, SDNn$) with these communication technologies, then the problem of a cost optimal hybrid communication model can be defined as, *To determine the technology combinations of intermediate nodes, $n_t = n_1, n_2 \cdots n_j$ with minimal cost subject to the QoS parameters of each technology and QoS requirement of the data packet generated by SCN of the smart building,* where n_1 represents the number of intermediate nodes with communication technology CT_1, n_2 represents the number of intermediate nodes with communication technology CT_2 and so on. The total number of intermediate nodes with different technologies required for the successful data packet delivery from source to destination is represented by n_t.

B. Cost Optimal Hybrid Communication Model

For solving the problem described in the previous section, we have formulated a non-linear optimization model which gives the optimal combination of intelligent devices with different technologies with minimum cost. If we have 'k' number of technologies and we need to operate the communication infrastructure for 'Y' years, the detailed model, presented below, will give the optimal combination of intelligent devices with different technologies at a minimum cost.

Minimize:

$$C = \sum_{t=1}^{k} \Big[n_t \times (I_c(t) + (\delta_t \times Y \times 12) + \big(C_t \times Y \times P_f \times (N_r + 1)\big)\big) + Y \times (C_i(t))^{(n_{SCN}+n_t)} \Big] \quad (1)$$

Subject to:

$$\sum_{t=1}^{k} \Big[(n_t - 1) \times r_t \times (1-p)^2 \Big] \geq D \quad (2)$$

$$N_r + 1 \geq \frac{1}{(1-p)} \quad (3)$$

$$\sum_{t=1}^{k} \big[(N_r + 1) \times (l_{link} + \tau + \gamma) \times n_t \big] \leq L \quad (4)$$

$$\sum_{t=1}^{k} \big[(n_t - 1) \times p \big] \leq Rel \quad (5)$$

$$n_t \geq 0 \quad (6)$$

$$0 \leq p < 1 \quad (7)$$

$$Max(b_{link}) \leq Min(B_t). \quad (8)$$

The objective is to minimize the sum of the overall costs which include installation, communication, maintenance and information capacity requirement for different technologies as shown in equation (1). The information capacity requirement cost is a measure of the information holding capacity of each technology and the efficiency to aggregate the data from different smart buildings and the intermediate devices. This cost exponentially decreases with the increase in the number of intermediate devices, since more devices offer an improved result for the information capacity requirement of the system as well as the data aggregation. Constraint in equation (2) shows the relationship between the variation of connectivity range and the probability of link unreliability. The concept that the path loss is related to the connectivity range by inverse square law is used to model the constraint in equation (2). This constraint ensures the single hop or multi hop connectivity from the source to the destination. The expression in equation (3) specifies the number of required data re-transmissions according to the probability of link unreliability. Constraint in expression 4 restricts the packet latency with regard to the link latency, transmission latency, and reception latency for the combination of intelligent devices with different technologies. Constraint in equation (5) restricts the increase in the number of hops with the increase in the link unreliability, by the introduction of a reliability factor '*Rel*'. Equation (6) gives the bounds for the number of intelligent devices. Constraint in equation (7) limits the value of probability of link unreliability, '*p*', between 0 and 1. Constraint in equation (8) limits the maximum flow bandwidth of the packets within the minimum flow bandwidth of the technology combination. Table I gives the list of notations used in this work and its descriptions.

TABLE I
LIST OF NOTATIONS AND ITS DESCRIPTIONS

Notation	Description
δ_t	Maintenance cost for an intelligent device per month
C_t	Cost of communication for a technology
N_r	Number of re-transmissions
I_c	Installation cost of an intelligent device
l_{link}	Data latency experienced in the link
τ	Delay for transmitting a packet from an intelligent device
γ	Delay for receiving the packet from an intelligent device
r_t	Communication range based on the technology
D	Maximum distance between source and destination
Y	Number of years
P_f	Frequency of packet transmission
n_t	Number of intelligent devices with technology 't'
$C_i(t)$	Cost of information capacity requirement for technology 't'
n_{SCN}	Number of smart buildings in microgrid
n_t	Number of intelligent devices with technology 't'
p	Probability of communication link unreliability
b_{link}	Flow bandwidth for the data packet
B_t	Maximum flow bandwidth of the technology
L	Latency allowed for the data packet to reach its end destination
Rel	Reliability factor

C. Recursive Algorithm for Cost Optimal Combination of Communication Technology (RACOCCT) for Smart Distribution Grid

The non-linear optimization formulation of the cost optimal hybrid communication model described in the previous section gives the cost optimal combination of technologies for the most distant branch of the power grid. However, a radial distribution grid has many bifurcations from the main branch of the grid. For such a radial distribution grid topology, a recursive algorithm can find the cost-optimal combination of intermediate intelligent devices. The pseudocode for RACOCCT is shown in the algorithm 1.

For the algorithm RACOCCT, the Power Grid Topology (PGT), the opted communication technologies (CT), the envisaged life-time of the smart grid (Y), the frequency of the chosen data packet (P_f), the allowable latency of the chosen data packet (L), the bandwidth requirement of the chosen data packet (B), the probability of link unrealiability (p) and the reliability constant (*Rel*) are given as inputs. Initially, the algorithm identifies the most distant branch in the inputted PGT. Then for this branch, the function FINDOPTVAL() inside the function FINDIDC() runs the optimization model and finds the optimal communication technology combinations of intermediate devices. The function FINDOPTVAL() finds out the total cost value for the selected communication technologies. Thereafter, the function FINDOPTVAL() finds the minimum cost value and the corresponding technology combinations, iteratively. This function checks whether all the constraints are satisfied or not. If all the constraints are satisfied, then the function FINDOPTVAL() returns the cost-optimal solution. Otherwise, it returns no feasible solution. The function GETCOMMDET() acquires the cost, bandwidth, communication range and latency details of each communication technology potentially to use for the PGT. After returning

Algorithm 1 RACOCCT

Input 1: PGT; Y; P_f; L; B
Input 2: CT_t for $t = 1, 2 \ldots k$; $p = 0, \ldots 1$; Rel
Output: n_t for $t = 1, 2 \ldots k$; C
Get the longest Branch (LB) of PGT
function FINDIDC(Input 2)
  for $CT_1, CT_2, \ldots CT_t$ **do**
    function GETCOMMDET(CT_t)
    end function
  end for
  function FINDOPTVAL(Input 2)
    for $(i = 0; i < numIteration; i++)$ **do**
      for $(t = 1; t < k + 1; t++)$ **do**
        $C = [n_t \times (I_c(t) + (\delta_t \times Y \times 12)$
        $+(C_t \times Y \times P_f \times (N_r + 1)))$
        $+Y \times (C_i(t))^{(n_{SCN}+n_t)}]$
        Check the constraints:
        $[(n_t - 1) \times r_t \times (1 - p)^2] \geq D$
        $N_r + 1 \geq \frac{1}{(1-p)}$
        $[(N_r + 1) \times (l_{link} + \tau + \gamma) \times n_t] \leq L$
        $[(n_t - 1) \times p] \leq Rel$
        $Max(b_{link}) \leq Min(B_t)$
        if All constraints satisfied **then**
          $C_{tot} = C_{tot} + C$;
        else
          No feasible solution
        end if
      end for
      $C_i = C_{tot}$;
      $n_t(i) = n_t$;
    end for
    Find $Min(C_i)$ and corresponding n_t
    Return (C_{tot}, n_t for $t = 1, 2 \ldots k$)
  end function
  Populate $Branch_i^j$ for $j = 1, 2 \ldots l$ and for $i = 1, 2 \ldots h$
  for i and j **do**
    if $Branch_i^j$!= 0 **then**
      function FINDIDC(Input 2)
      end function
    else
      Exit
    end if
  end for
end function

the cost-optimal n_t for $t = 1, 2, \ldots, k$ and the optimal cost value, the function FINDIDC() populates the branches of the identified longest branch. The same function FINDIDC() is recursively called until the optimal cost of technology combinations, n_t for $t = 1, 2, \ldots, k$ values is determined for all branches of the longest branch and for all sub-branches. Once the radial PGT ends or all the branches are covered, the RACOCCT exits and ends the function.

RACOCCT offers a provision to designers to choose diverse communication technologies for varying branches and sub-branches of the PGT. The probability of link unreliability and the reliability constant can be selected depending upon the varying geographic features and propagation effects for different branches and sub-branches of the given PGT.

VII. SIMULATION RESULTS AND DISCUSSIONS

In this section, we present the simulation of the optimization model defined from equations (1) to (8) and the simulation of RACOCCT described in the previous section. The simulation of the optimization model yields the optimal combination of technologies with minimum cost for a specific data packet.

A. Simulation Environment

The maximum pole to pole distance varies between 40m and 50m in a traditional power grid structure. Therefore, we considered a microgrid having equi-distant poles with a 40m maximum pole-to-pole distance. The maximum distance between each SCN and the MCS was assumed as 3Kms. The length of Consumer Data Packet (CDP) generated by each smart building was assumed as 10kbps. The maximum latency allowed for CDP is assumed as one hour for the simulation.

For the simulation purpose, three technologies, namely ZigBee, Wi-Fi and Cellular were considered. However, the model is capable of handling ‘1’to ‘k’variations of technologies with diverse QoS metrics. The connectivity range for ZigBee, Wi-Fi and Cellular technologies are considered as 40m, 120m and 10Km, respectively. For the simulation, we have considered the flow bandwidth for ZigBee, Wi-Fi and Cellular as 250kbps, 11Mbps and 75Mbps, respectively [36]. The maximum latency allowed for CDP is one hour. In this research work, the tool Excel Solver is used to solve the cost-optimal model for a branch of microgrid. The solver took 50 iterations on an average to determine the optimal solutions for the model.

B. Simulation Parameters

The QoS metrics of communication architecture are bandwidth, delay, throughput, data rate, packet loss, and error rate. The variations of cost for transmitting each type of packet with the probability of link unreliability, the bandwidth consumed, and the communication latency experienced for the three communication technologies: ZigBee, Wi-Fi and Cellular are studied in this work. The bandwidth requirement depends on the number of SCNs connected, and latency depends on the maximum distance between source and destination. The probability of link error was varied up to 0.9. The number of SCNs in a microgrid varied up to a maximum of 25. The maximum distance between a SCN and MCS varied up to a maximum of 3Km. For the simulation, we have assumed CDP packet transmission with the infrastructure installation duration of 10 years. The installation cost for ZigBee, Wi-Fi and Cellular are selected as 15USD, 75USD and 250USD respectively.

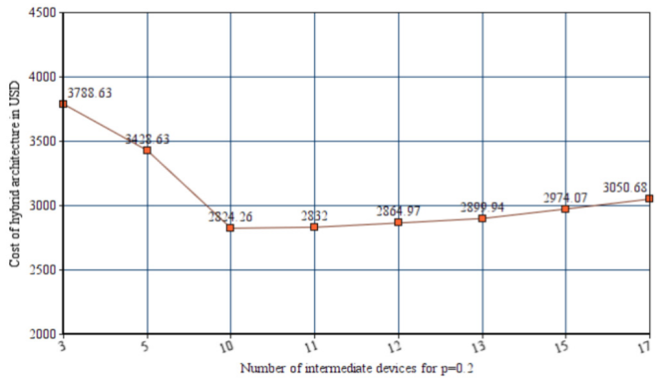

Fig. 3. Cost versus number of intermediate devices for $p = 0.2$.

TABLE II
TECHNOLOGY COMBINATIONS FOR VARYING NUMBER OF INTERMEDIATE DEVICES FOR $p = 0.2$

Number of intermediate devices	ZigBee	Wi-Fi	Cellular
3	0	0	3
5	0	2	3
10	1	7	2
11	3	6	2
12	4	6	2
13	5	6	2
15	7	6	2
17	9	6	2

C. Results and Discussions

The optimization model provides a cost-increasing trend when the number of intermediate devices is minimal or very high. The model tries to find an optimal number of combinations of intermediate devices within this trend. The results in Figure 3 show the cost variations in USD with respect to the number of intermediate devices for the hybrid architecture of a microgrid while keeping the probability of link unreliability $p = 0.2$. The plot shown in Figure 3 shows total number of intermediate devices varying between 3 and 17. From the plot we can find that the minimum cost value is obtained when the total number of devices is 10. That means, the model converges to the optimal value of the cost which is 2824USD for 10 years when the number of intermediate devices becomes 10. For any initial point, the model satisfies the equality and inequality constraints in finite time. This demonstrates the optimality of the results obtained from the model. The table II shows the feasible technology combinations for different number of intermediate devices when $p = 0.2$. Out of which the cost-optimal technology combination is one ZigBee device, seven Wi-Fi devices, and two Cellular devices satisfying all the constraints in the model. To demonstrate the optimality of the results obtained from the model, we have graphically solved the model in case of the probability of link unreliability $p = 0.2$. Figure 4 illustrates the graphical representation of the optimization problem with the probability of link unreliability $p = 0.2$. The three dimensional plot shows the feasibility region with the decision variables number of Zigbee devices, number of Wi-Fi devices and number of Cellular devices as the X, Y and Z co-ordinates. The optimal point lies in one of the corner of the feasibility region which is marked in the figure. While solving the same optimization problem with Excel Solver, the optimal point is the same as that we got by graphical method of solving. Therefore, it is clear that the optimization problem is always giving the optimal solution from the set of feasible solutions.

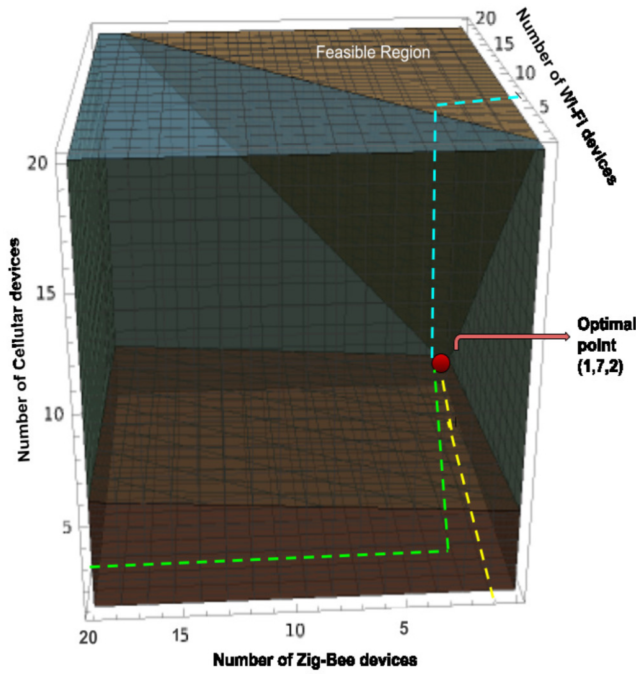

Fig. 4. Illustration of feasible region and optimal point for $p = 0.2$.

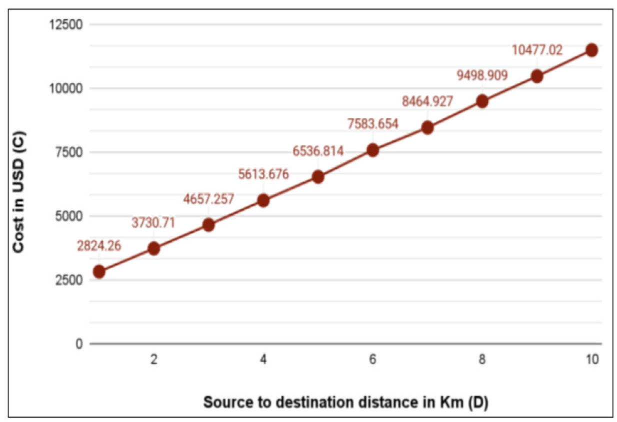

Fig. 5. Cost versus source to destination distance for $p = 0.2$.

The simulation result in Figure 5 displays the variation of cost with the source to destination distance variation for the probability of link unreliability, $p = 0.2$. As the distance D varies from $1Km$ to $10Kms$, the total cost is linearly increasing. Table III shows the technology combinations of the intermediate devices for varying distances between the source and the destination for probability of link unreliability, $p = 0.2$. We can find a linear increase in Cellular devices when the distance D varies from $1Km$ to $10Kms$. The simulation result in Figure 6 shows the variation of cost with

TABLE III
TECHNOLOGY COMBINATIONS FOR VARYING SOURCE TO DESTINATION DISTANCE FOR $p = 0.2$

D in Km	ZigBee	Wi-Fi	Cellular
1	1	7	2
2	2	12	3
3	2	8	5
4	3	13	6
5	2	9	8
6	1	5	10
7	2	10	11
8	1	16	12
9	1	12	14
10	2	17	15

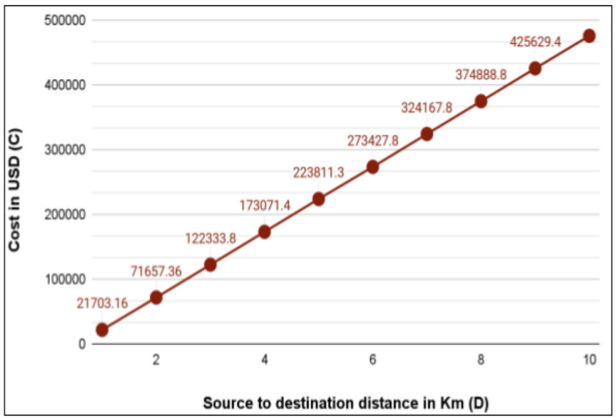

Fig. 6. Cost versus source to destination distance for $p = 0.8$.

TABLE IV
TECHNOLOGY COMBINATIONS FOR VARYING SOURCE TO DESTINATION DISTANCE FOR $p = 0.8$

D in Km	ZigBee	Wi-Fi	Cellular
1	1	251	1
2	0	222	29
3	3	191	57
4	3	161	85
5	3	131	113
6	0	112	140
7	0	82	168
8	3	51	196
9	3	21	224
10	1	1	251

the varying source to destination distance for probability of link unreliability, $p = 0.8$. In this case to establish reliable communication, more WiFi and Cellular devices are required. Thus, we can find an increase in the total cost compared to the plot for $p = 0.2$ which is shown in Figure 6. The technology combinations for varying source to destination distances for probability of link unreliability, $p = 0.8$ is shown in table IV. We can find an exponential increase in Cellular devices and an exponential decrease in Wi-Fi devices when the distance D varies from $1Km$ to $10Kms$.

The simulation result in Figure 7 exhibits the variation of cost with the changes in probability of link unreliability for $D = 1Km$. Here the model is trying to accommodate a greater number of devices for the successful packet transmission from source to destination. Therefore, the total cost is exponentially increasing after $p = 0.7$. The plot in the Figure 8 displays

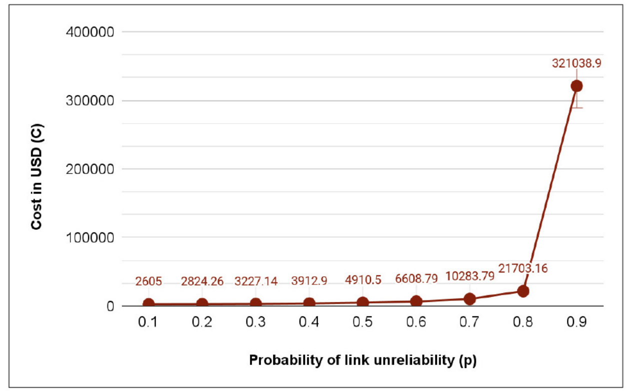

Fig. 7. Cost versus probability of link unreliability for $D = 1Km$.

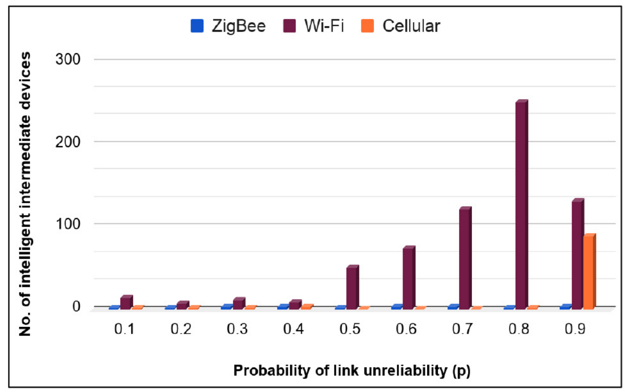

Fig. 8. Number of intermediate devices combination versus probability of link unreliability for $D = 1Km$.

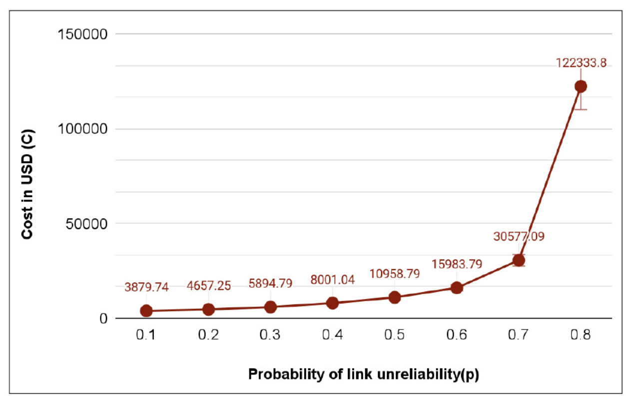

Fig. 9. Cost versus probability of link unreliability for $D = 3Kms$.

the optimal combination of technologies with the variation of probability of link unreliability for $D = 1Km$. In the plot, we can find that the Wi-Fi technology is dominant for the entire range of probabilities of link unreliability. The lower cost of Wi-Fi technology compared to Cellular and the reliable end-to-end data delivery of Wi-Fi compared to ZigBee is one reason for the Wi-Fi dominance. When $p = 0.9$ the presence of Cellular technology is highly visible in the optimal combinations.

The simulation results, shown in Figures 9 and 10, display the variation of cost, with the probability of link unreliability and the cost-optimal combination of technologies with the

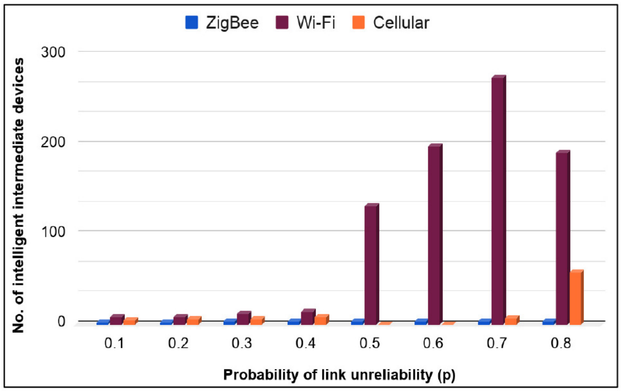

Fig. 10. Number of intermediate devices combination versus probability of link unreliability for $D = 3Kms$.

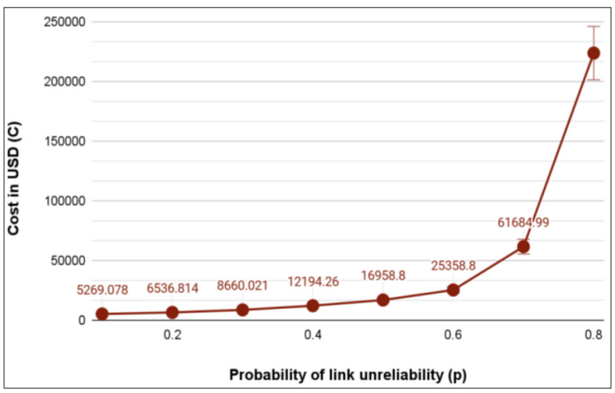

Fig. 11. Cost versus probability of link unreliability for $D = 5Kms$.

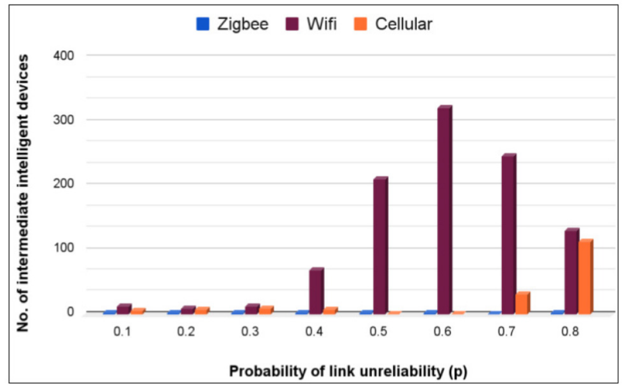

Fig. 12. Number of intermediate devices combination versus probability of link unreliability for $D = 5Kms$.

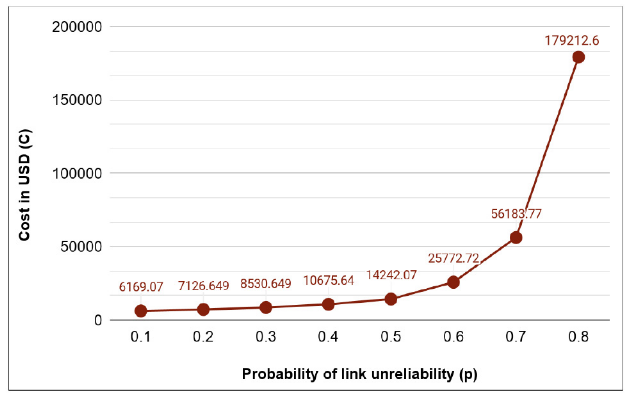

Fig. 13. Cost versus probability of link unreliability for $D = 3Kms$ with increased prices for Wi-Fi and Cellular.

probability of link unreliability respectively for $D = 3Kms$. From $p = 0.5$ onwards, the total cost increases exponentially. When the distance between the source and the destination ‘D’increases, the total cost for hybrid communication architecture also increases for the varying values of probability of link unreliability. In Figure 10, the model is giving a balanced combination of technologies for the range of probabilities of link unreliability from $p = 0.1$ to $p = 0.4$. When $p = 0.5$ onwards, a sudden increase in the intermediate devices with Wi-Fi technology is visible. It is evident that the model picks the best technology suitable to lower the cost and at the same time to ensure the successful end-to-end data packet transmission. Intermediate devices with Cellular technology make a prominent presence when $p = 0.1$ to $p = 0.4$ and at $p = 0.9$. At lower values of ‘p’, the choice of fewer devices to cover more distance indicates the prominence of Cellular technology.

The simulation result, shown in Figure 11, displays the variation of cost with the probability of link unreliability for $D = 5Kms$. From $p = 0.5$, we find an exponential increase in the total cost. When the distance between the source to the destination ‘D’increases from 3Kms to 5Kms, the total cost for hybrid communication architecture also increases for the varying values of probability of link unreliability. The simulation result in Figure 12 shows the cost-optimal combination of technologies by varying the probability of link unreliability for $D = 5Kms$. In Figure 12, we can find the model is giving a balanced combination of technologies for the intermediate devices from $p = 0.1$ to $p = 0.3$. When $p = 0.4$ onwards a sudden increase in Wi-Fi technology is visible. This is due to the fact that the model picks the best technology suitable to reduce the cost and at the same time to ensure the successful end-to-end packet transmission. The intermediate devices with Cellular technology make a prominent presence from $p = 0.1$ to $p = 0.3$ and also from $p = 0.7$ to $p = 0.8$. The model fails to give feasible values from $p = 0.9$ onwards.

To study the variation in the optimal combination of technologies with increased prices for Wi-Fi and Cellular devices, the simulation parameter installation cost ‘I_c’for the devices using Wi-Fi and Cellular technologies are escalated to 150USD and 1000USD respectively. The results are plotted in Figures 13 and 14. The plot shows cost versus probability of link unreliability for $D = 3Kms$ in the Figure 13. We can find an exponential increase in total cost from $p = 0.4$ onwards. In both of the plots shown in Figures 9 and 13, we find an exponential increase in the total cost with respect to increase in ‘p’.

The change in the combination of devices with respect to variation in probability of link unreliability for $D = 3Km$ with increased prices for Wi-Fi and Cellular is shown in Figure 14. Until the probability of link unreliability reaches 0.6, the model gives predominance to ZigBee since it is the most cost effective technology. The number of ZigBee devices

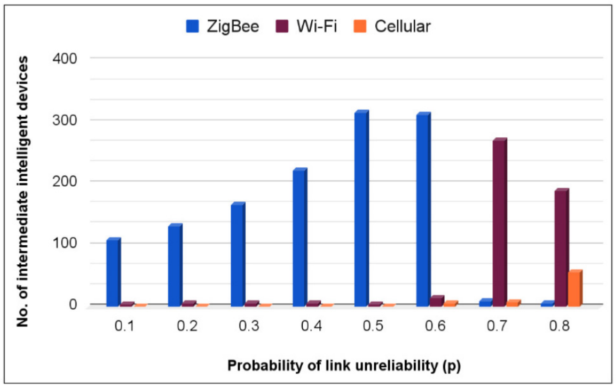

Fig. 14. Number of intermediate devices combination versus probability of link unreliability for $D = 3Kms$ with increased prices for Wi-Fi and Cellular.

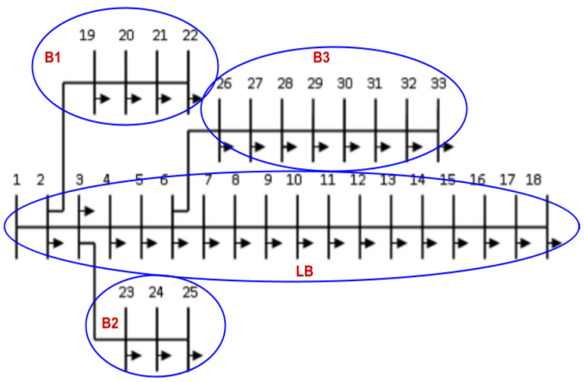

Fig. 15. IEEE 33-bus radial distribution system.

increases exponentially until $p = 0.5$. At $p = 0.6$ the number of ZigBee devices is almost the same as at $p = 0.5$ with a small increase in the Wi-Fi and Cellular devices as shown in Figure 14. After $p = 0.6$, the dominance shifts to Wi-Fi. At $p = 0.8$, a significant increase in Cellular devices is visible.

Consequently, the model helps us to understand the cost optimal combinations of technologies for a radial distribution grid. The model gives a representation of the total cost for the optimal combinations for a specific probability of link unreliability 'p'. The probability of link unreliability can be derived from different path loss models for the geographical region where the deployment of the devices is planned in the distribution grid.

D. Simulation Study and Results of RACOCCT

The Standard IEEE 33-bus radial distribution system has been taken as an example for power grid topology(PGT) to illustrate the simulation study of RACOCCT [37]. As shown in Figure 15, the longest branch (LB) has buses from 1 to 18. The first branch B1 starts from bus 2 and has buses from 19 to 22. The second branch B2 starts from bus 3 and has buses from 23 to 25, and finally the third branch B3 starts from bus 6 and has buses from 26 to 33.

We have implemented RACOCCT in Java, and the code calls the Excel solver to solve the optimization formulations. For the simulation study of RACOCCT, we have considered the consumer data packet (CDP) transmission from source to

TABLE V
INPUT PARAMETERS FOR EACH BRANCH OF PGT

Branch ID	p	Source Bus No.	Destination Bus No.	D in Km
LB	0.3	1	18	12
B1	0.7	19	22	3
B2	0.4	23	25	2.5
B3	0.6	26	33	5

TABLE VI
OUTPUT OF RACOCCT WITH GIVEN INPUT PARAMETERS

Branch ID	No. of ZigBee devices	No. of WiFi devices	No. of Cellular devices	Cost in USD
LB	628	6	0	26509.64
B1	10	271	7	56183.76
B2	189	6	0	9388.64
B3	305	12	19	48447.67

destination with a transmission frequency of one minute and with latency constraint of one second. The infrastructure installation duration for all the branches is 10 years. We have varied some of the input parameters among the branches in PGT which is shown in table V.

ZigBee, WiFi and Cellular communication technologies are selected for all branches of PGT. The algorithm RACOCCT first chose the longest branch in PGT which is LB for determining the optimal combination of communication technologies for intermediate devices. Thereafter, branches B1, B2, and B3 are successively selected for recursively determining the optimal combination of intermediate devices.

The result of RACOCCT for the given PGT and the input parameters are shown in table VI. For the branches LB and B2, when there are more ZigBee devices compared to the number of Wi-Fi devices, the model ignores the Cellular technology. This is due to the fact that in both the cases of LB and B2, the probability of link unreliability is less than 0.5. We can see the inclusion of Cellular devices for the branches B1 and B3. The infrastructural cost is highest in the case of the branch B1, due to the fact that the probability of link unreliability is highest for branch B1 compared to other branches even though the source to destination distance is comparatively short. The infrastructural cost is comparatively low in case of the branch LB even though it is the longest branch which is due to the lowest value of the probability of link unreliability. Thus RACOCCT can yield the cost-optimal combination of communication technologies for intermediate devices for a given power grid topology.

VIII. CONCLUSION

In this paper, we presented an overview of smart distribution architecture with networked micrograms and the need of a hybrid communication network for the data exchange inside the microgrid. To ensure the real-time spatio-temporal data exchange between the power grid elements, a cost-optimal model is proposed in this work. It analyses the combination of intermediate devices from a source to destination inside the microgrid to derive the optimal cost. This model takes into account the QoS metrics such as data packet latency, bandwidth requirement, link reliability, packet drops and communication range of the technology were taken into account in the formulation. The proposed algorithm, the Recursive Algorithm for Cost Optimal Combination of Communication Technology (RACOCCT) yields the cost-optimal solution recursively for a given power grid topology. The model has been simulated using Solver. The results were evaluated using ZigBee, Wi-Fi and Cellular technologies. The results of the simulation study illustrated the cost-optimal combination of technologies (ZigBee, Wi-Fi, and Cellular) for varying probability of link unreliability. The results of the simulation study of RACOCCT demonstrated its capability to derive the cost-optimal combination of intermediate devices for a given power grid topology.

As to future work, we intend to modify the proposed model in order to determine the optimal location for the placement of the intermediate devices in the power grid topology. Furthermore, we plan to enhance the RACOCCT algorithm by evaluating its performance in extreme environmental scenarios having extended variabilities in the link performance in each branch of the power grid topology.

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