Verification of Data Sparsification Technique in Smart Grid Communication

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Abstract: - Dealing with data transmission in smart grid networks is one of the most challenging topics in telecommunications industry. Wireless mesh network (WMN) and Power line communication (PLC) are suitable technology for distributed smart grid communication; both connections are lossy connections. Network virtualization (NV) is a promising innovation to bolster customized end-to-end execution of different services in real-time. In this paper, a NV-based structure is proposed for smart grid communication, where real-time services are upheld by virtual networks that are mapped to both physical systems at the same time. Since the VN mapping and subcarrier task issue is nondeterministic polynomial-time hard, heuristic solutions are implemented. To reduce the complexity of the system, data sparsification algorithm is applied to the input of the system. The results with the data sparsification and the results without the data sparsification are compared in the proposed work. Simulation results show the adequacy of our proposed technique.

Key-Words: - network virtualization, OFDMA-based wireless mesh network, power line communication, smart grid, data sparsification

1 Introduction

The development in the power conveyance structure is mentioned by Smart Grid. The information exchange is essential in smart grid as the ultimate objective is to control and manage the framework. For the distribution grid, Wireless Mesh Networks (WMN) [2] and Power line communication (PLC) [3] seem to be the convenient network options. Due to the higher network pocket loss, both the networks suffer from bit error and packet loss because of interference and attenuation.

Network Virtualization (NV) [4], [5] is a promising innovation, which offers customized end-to-end execution of different services. In this technique, the virtual networks (VNs) can work separately while being disengaged with one another. This virtual network works on mutual substrate network (SN). To meet the prerequisites of different services, a communication system is outlined for the smart grid which uses NV technology. The orthogonal frequency division multiple access (OFDMA) is assigned as multiple access scheme for the WMN in NV.

An experiment based arrangement is produced, for the VN mapping and subcarrier assignment issue which is nondeterministic polynomial time (NP) hard. This solution is developed to take care of the assignment issue proficiently and adequately. The other benefit of this solution is the reliability of real-time services and the expansion of the best-effort traffic with fairness can be ensured. This paper also focuses on the situation of VN embedding (VNE) in diverse SNs for the improvement of transmission diversity. To reduce the complexity of the system, a data compression algorithm is introduced in the proposed work.

The objectives of our proposed work are as follows:
1. To plan an NV-based communication system for smart grid, which carry the applications with various quality of service (QoS) requirements.
2. To plan an OFDM-based WMN for NV and upgrade the transmission diversity.
3. To ensure real-time service delay and reliability by proposing a VNE approach in diverse SNs with increased transmission diversity.
4. To develop an experience based answer for comprehend the VN mapping and subcarrier task issue, which is NP hard.

In this paper, we have followed the same procedure as studied by Pin Lv et al. [1] and have applied the data sparsification algorithm at the input to get the better results and to reduce the complexity.

2 Background

An electric grid is a network of synchronized power providers and consumers that are connected by transmission and distribution lines and operated by one or more control centers. In light of need and security prerequisites in real applications, the corresponding services of these information sources can be ordered into four isolated zones, including control, operation, management and data. The four zones can be parceled into control and operation division (COD) and management and data division (MDD).

In real organizations, the smart grid information framework is made out of heterogeneous systems. Subsequently, using wireless systems and/or PLC systems is an economical and flexible approach to transmit data in the distribution network. Besides, because of their restricted transmission ranges, it is important to arrange wireless or PLC systems into multi-hop systems, which causes higher transmission latency. Hence, it is trying to fulfill the delay and unreliability limitations of the real-time services of COD in wireless or Power Line communication (PLC) systems.

By looking at the attributes of the PLC technologies, the multicarrier NB PLC is the most fitting technology for the case concentrated on in this paper. Time is isolated into edges, which are composite units of deliberation for channel use.

Let "∈" _"p" be the packet error rate (PER) of PLC and h be the hop count of a terminal to the base node. Here we have assumed the traffic loads of the control and operation services to be not all that substantial that the CFP can simply be apportioned while being asked. The success probability of control message transmission over PLC (meant by "P" _"CP") is,

$$P_{CP} = (1-\epsilon_p)^h \tag{1}$$

In this paper, transmission is assumed to be unsuccessful on the off chance that it is collided. To dissect the execution of CSMA/CA system, a precise model is set forward by Bianchi in [18]. The conditional collision probability, p of a terminal can be settled from the accompanying nonlinear framework:

$$\tau=\frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \tag{2}$$

$$p=1-(1-\tau)^{n-1} \tag{3}$$

The variable τ is the probability that a station transmits in a haphazardly picked space time. The parameter W levels with the minimum contention window CW_{min} while m is the maximum back off stage such that CW_{max}= 2mW. In this manner, the parameters in (2) are W=15 and m=6. The parameter n in (3) indicates the number of the stations that go after the channel. The analysis in [18] depends on saturation conditions, i.e., every station dependably has packet to transmit. The successive transmission probability $S_{P(i)}$ can be defined by $S_{P(i)} = 1 - p$, where p is the collision probability of the i^{th} jump. The success probability of operation message transmission over PLC P_{OP} can be defined as,

$$P_{OP}=\prod_{i=1}^{h}(S_{P(i)}(1-\epsilon_p)) \tag{4}$$

Wireless Mesh Network (WMN) gives higher transmission capacity and bit rate compared with the PLC system. Subsequently, in our outline, the WMN needs to bolster the VN of the MDD other than the VNs of the COD. All the more particularly, a TD needs to bolster a couple VNs.

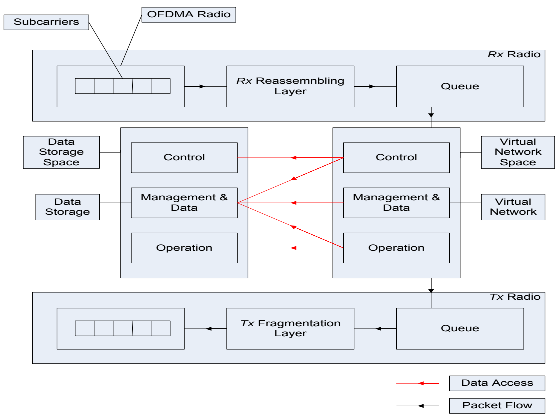

Fig. 1. *OFDMA-based mesh node design for smart grid communication*

Keeping in mind the end goal to granularly allot assets to VNs, OFDMA is utilized as the multiple access schemes for WMN in the framework. As the wireless radio in node design is half duplex, a VN can't transmit when another VN is accepting. Therefore the node ought to be furnished with two radios: One is particularly to transmit and the other is particularly to receive. The WMN construction modeling is delineated in figure 1.

To abstain from disregarding the acknowledgement (ACK) plan, the ACK transmission is seen as atomic operation together with information gathering. After a short inter-frame dispersing for R_"x" /"T" _"x" exchanging, the "R" _"x" radio will send ACKs. Along these lines, each VN can begin transmission quickly without sitting tight for other VNs' reception. To dispense with mutual interference, WMN is sorted out into a hierarchical structure.

At the point when there are various radios on the same wireless node, the out-of-band (OOB) [19] impedance impact for the most part exists, configuring the working frequencies of the two radios into two groups individually can dispose of mutual interference successfully [20]. This is how the OFDM based WMN is designed for network virtualization. On the premise of such outline, the WMN is sorted out into a hierarchical structure. Consequently, the traffic must be exchanged between neighboring levels.

Since each VN has its committed subcarriers for transmission, the transmission will not endure collision or back-off. In the event that a mistake happens at the recipient, the transmitter will not get the ACK. In the wake of holding up a sure timeframe it will retransmit the packet. To enhance the transmission diversity, various subcarriers can be used to transmit the same packet simultaneously. In this paper, we concentrate looking into it that the CC is outfitted with two radios.

Network virtualization (NV) based system is a promising procedure to defeat the deficiencies of the Internet by permitting various heterogeneous systems to coincide on a common Substrate Network (SN). These heterogeneous networks are alluded to as Virtual Networks (VNs), which supply customized end-to-end services. Every substrate node can bolster various virtual nodes, and various VNs work autonomously without meddling with one another. Subsequent to the smart grid requires differing applications, the musings of NV is exceptionally suitable for the smart grid communications.

That is, diverse applications work as particular VNs on communication infrastructures. After suitable resource allocation, these VNs can run freely with no mutual interference. Precise and heuristic optimization algorithms for the provisioning of VNs including different infrastructure providers are introduced in [12]. The VNs are mapped to numerous heterogeneous SNs at the same time. In the connection of the smart grid, both networks co-exist as the SNs in the meantime. Subsequent to the transmission media of the two PHY systems are distinct; they likely have disparate topologies and diverse transmission characteristics. The VNs are installed into the two heterogeneous SNs according to their diverse demands. This element makes the VNE in smart grid an exceptional and testing research issue.

Not at all like those current VNE arrangements, the node mapping in a smart grid is deterministic, as the communication terminals of a service are essentially chosen by specified electric devices; then again, in the environment of the smart distribution grid, there are two SNs accessible for the link mapping. The transmission diversity and reliability can be upgraded by mapping the virtual link of the VN to substrate paths in distinctive SNs when any single substrate path in the SNs cannot meet the prerequisites. The PLC and WMN are assumed to be independent transmission media.

As PLC system is fit for the services with little data volume, VNs for control and operation administrations are created in the COD and inserted into heterogeneous systems to ensure their necessities; the management and data services in the MDD are merged into one VN. VN is mapped to the WMN, which offers best-effort transmission service.

2 Data Sparsification

To reduce the complexity of the system, an algorithm of data sparsification is applied on the input. According to the algorithm, maximum sparsity is achieved by considering the CPI values pertaining to each block. Invariably this would result in considerable loss of information in the signal. The input is divided into 8×1 samples and discrete ratio transform (DRT) is applied to each block and DRT spectrum is obtained. Each block spectrum would consist of 8×1 samples.

The first element in each block spectrum is its CPI and the remaining seven elements its spectral components. Now, sparsing is carried out in each block by forcing all seven elements in a block other than the CPI to the value 0. The positions of all 0's are a priori known and hence one can compress the spectrum of the original length to the CPI sequence of its 1/8th length. This reduced CPI sequence is stored instead of the original voice data sequence. One can decompress this CPI sequence by introducing 0's in appropriate places and make it a sequence of the original length. Then the uncompressed sequence is decoded by applying IDRT to it.

2.1 Data Compression (pseudocode):

Procedure: 1 // Converting the input data sequence into the 8×1 data blocks

(1) Input: Original data sequence
(2) Divide the input data sequence into the 8×1 data blocks.

Procedure: 2 //Getting the DRT spectrum and apply the data sparsification
(3) Create an operating matrix R_k
(4) **for** each data block **do**
$Y_m = R_m X_m$; // DRT spectrum
(5) **for** each data block of the DRT spectrum **do** Make all the values of the data block zero other than the CPI; Create a sequence of the CPIs;
(6) New input: Sequence of CPIs

Procedure: 3 //Applying IDRT at the output
(7) Place the zeros at the appropriate places to get the sequence of same length of that of the input and make the data block of size 8×1 with the first value as the CPI and all the other elements to be zero.
(8) **for** each data block **do**
$\tilde{X}_m = \frac{1}{2}[R_m^T Y_m] = [x_m^1 \ \ x_m^2 \ldots \ \ x_m^i]^T$; // reconstructed data sequence
(9) error=input data sequence-reconstructed data sequence;

3 Problem Formulation

The substrate WMN and the PLC framework are both ready to be disconnected into weighted undirected graphs, which are meant as $G_w = (N, E_w)$ and $G_p = (N, E_p)$ separately, where N is the node set and E_w and E_p are edge sets of the WMN and PLC systems respectively. The two systems have the indistinguishable node set N where $|N| = n$. There is one CC (denoted by n_0) and (n-1) TDs (denoted by n_i where i=1, 2… n-1) in the set N. In this framework each node contains of two attributes, i.e. $S_t(i)$ and $S_r(i)$, which shows the subcarrier numbers of T_x and R_x radios respectively.

Each $e_w \epsilon E_w$ is associated with a real number $R_{ew} \epsilon$ [0, 1], which is the reliability of the lossy wireless links. The reliability of PLC link $e_p \epsilon E_p$ is figures as R_{ep}= 1-ϵ_p where ϵ_p is the Packet Error Ratio (PER) of the PLC link. The bit error rate of both WMN and PLC are represented as r_{ew} and r_{ep} respectively.
Except for the CC, each node has three VN requests. A control service request and an operation service request is communicated by a triple $c(i) = (L_c(i), D_c(i), R_c(i))$, and $o(i) = (L_o(i), D_o(i), R_o(i))$, respectively. Here $L(i)$ is the dominated length of the control message, $D(i)$ is its delay request and $R(i)$ is the reliability request. The actual transmission success probability of $c(i)$ and $o(i)$ after being mapped to the heterogeneous SNs is $P_c(i)$ and $P_o(i)$, respectively. An $n\times$ $(n$-$1)$ matrix $[s_c^t(i,j)]_{n\times(n-1)}$ and $[s_o^t(i,j)]_{n\times(n-1)}$ is used to keep the records of the T_x radio subcarrier assignment of the control services and operation services respectively. The term $s_c^t(i,j)$ and $s_o^t(i,j)$ in the matrix indicates the T_x-radio subcarriers that n_i allocates to $c(j)$ and $o(i)$ respectively.

Likewise, $n\times(n$-$1)$ matrix $[s_c^r(i,j)]_{n\times(n-1)}$ and $[s_o^r(i,j)]_{n\times(n-1)}$ keeps the records for the R_x-radio subcarrier assignment.
Every node likewise has a best-effort traffic request $b(i)$. The real fulfilled part of the best-effort traffic request is $f(i)$ after the VNE process. An $n\times$ $(n$-$1)$ matrix $[s_b^t(i,j)]_{n\times(n-1)}$ is used to keep the records of the

T_x radio subcarrier assignment of the best-effort services. Likewise, $n\times$ *(n-1)* matrix $[s_b^r(i,j)]_{n\times(n-1)}$ keeps the records for the R_x-radio subcarrier assignment. The issue can be formulated as beneath [1]:

$$\text{Maximize } \sum_{i=1}^{n-1} f(i) \tag{5}$$

St.

$$P_c(i)\geq R_c(i), \qquad i=1, 2\ldots n\text{-}1 \tag{6}$$

$$P_o(i)\geq R_o(i), \qquad i=1, 2\ldots n\text{-}1 \tag{7}$$

$$f(i)\leq b(i), \qquad i=1, 2\ldots n\text{-}1 \tag{8}$$

$$\sum_{j=1}^{n-1} s_c^t(i,j)+\sum_{j=1}^{n-1} s_o^t(i,j)+\sum_{j=1}^{n-1} s_b^t(i,j)\leq S_t(i),$$

$$i=1, 2\ldots n\text{-}1 \tag{9}$$

$$\sum_{j=1}^{n-1} s_c^r(i,j)+\sum_{j=1}^{n-1} s_o^r(i,j)+\sum_{j=1}^{n-1} s_b^r(i,j)\leq S_r(i),$$

$$i=1, 2\ldots n\text{-}1 \tag{10}$$

These equations state that the actual satisfied part of the best-effort traffic request should be maximized such that the actual transmission success probability of c(i) will be more than the reliability request of control service on the node n(i). Also the actual transmission success probability of o(i) will be more than the reliability request of operation service on the node n(i). The total number of "T" _"x" -radio and "R" _"x" -radio subcarrier that "n" _"i" allocates to the control, operation and best-effort services will be less than the subcarrier number of the "T" _"x" radio and "R" _"x" -radio, respectively on node "n" _"i" .

In the situation when the fairness of the best-effort traffic is not considered, the satisfied best-effort traffic of some nodes rises to zero. In order to avoid such circumstances, Max–Min fairness is taken into account. For this objective, the difference between the maximum ratio of the actual satisfied part of the best-effort traffic request and the best-effort traffic request of each node and the minimum ratio of the actual satisfied part of the best-effort traffic request and the best-effort traffic request of each node should be minimized. The accompanying target ought to be added to the problem formulation as below:

$$\text{minimize } \left\{max\left(\frac{f(i)}{b(i)}\right)\text{-}min\left(\frac{f(i)}{b(i)}\right)\right\} \tag{11}$$

The complexity of this multi-objective optimization issue is NP hard. To take care of the issue effectively, we take a heuristic solution in to use.

3 Problem Solution

The first step of the heuristic solution is to figure the success probability of real-time services in the PLC network. The success probability of real-time service's transmission in PLC (signified by "P" _"PLC") can be figured by using equations (1) and (4).

In the second stage of the heuristic solution, subcarriers for real-time services in the WMN are relegated, which enhances the diversity and reliability. The integrated reliability of the transmissions in two SNs measures up to the probability that the transmission is successful in no less than one SN [1]. Taking into account the demand that the integrated reliability ought to be no not exactly the required reliability, we can get

$$1\text{-}(1\text{-} P_{PLC})\ (1\text{-} P_{WMN})\ \geq R_{req} \tag{12}$$

Where, P_{WMN} is the success probability in the WMN and R_{req} is the reliability request of the real-time service.

In the wake of acquiring P_{PLC} in the initial step, the success probability in the WMN can be registered as

$$P_{WMN}\geq\frac{R_{req}\text{-}P_{PLC}}{1\text{-}P_{PLC}} \tag{13}$$

As WMN in this system uses mesh topology, there are various routing paths to the CC form TD. By picking the routing path with the minimum single subcarrier expected transmission time the TD decreases the complexity of routing selection, which is ascertained as

$$\min \sum_{e \in p} \frac{L}{r_e} \quad (14)$$

Where, p is a routing path from the TD to the CC, e is a link in p, $r_e$is the single subcarrier bit rate of e, and L is the dominated packet length of the real-time service.

Once the routing path is determined, the T_x/R_x-radio subcarriers are assigned to the real-time service. The subcarrier assignment is directed in an iterative way, i.e., add one subcarrier to the link with the most minimal reliability at once until the reliability of the entire path accomplishes or surpasses P_{WMN}.

In the third step of the solution, the best-effort service throughput is maximized. At the point when the second step has been done, the remaining WMN is utilized for best-effort traffic. The remaining WMN can be stated as $G^* = (N,E^*)$. It is unique in relation to traditional maximal flow problem, subsequent to the capacity of an edge in our system might change with the usage of different edges if these edges share subcarriers. Two algorithms are assigned for getting the maximal best-effort service throughput.

The throughput maximization is proposed in algorithm 1.

The center thought of Algorithm 1 incorporates two stages. In the first stage, the link capacity is confined from top to bottom in the hierarchical structure. In the second stage the traffic is pushed from bottom to top. The primary stage abstain the traffic from being misled to the way in which upper links are having low capacity.

The primary stage is important on the grounds that it can abstain from misleading traffic to the way in which upper links are with low capacity. $O(|E^*|\bullet|N|)$ is the computing complexity of algorithm 1.

The input for the first algorithm is the remaining WMNG^*. For each $e \in E^*$, the capacity of the link in a routing path from the TD to the CC is marked. For each node n on the current level, the capacities of the lower links are set based on the capacities of its upper link from top level to the bottom level. Then for each node n on the current level, the maximum traffic is pushed to the upper nodes from bottom level to top level. The capacities of the relevant links are updated according to it. The output of this algorithm is the maximal throughput.

As the fairness is not taken into the consideration in the first algorithm, the satisfied best-effort traffic of few nodes rises to zero. The second algorithm is created to accomplish max-min fairness. A specific extent of the best-effort traffic is pushed to the CC by the node. The transmission comes up short in the case that mostly all the data have been transmitted or all the routing paths to the CC have been saturated. In such situation the node is expelled from the node set. The procedure rehashes until the node set gets to be void. Along these ways, the satisfied ratio of the considerable number of nodes increments consistently, and the gap between the maximal ratio and the minimal one is minimized. The complexity of Algorithm 2 is $O(|N|)$.

The input of the second algorithm is the remaining WMN G^* and the proportion of the pushed traffic P_{rop}. For each $n_i \in N$, the $D_i \bullet P_{rop}$ is attempted to push to n_0, while $N \neq \phi$. If the attempt is success than the remaining WMN will be updated otherwise the node will be removed from the node set. The output of this algorithm will be the achieved throughput.

4 Simulation Results

Simulations are directed to assess the execution of our proposed NV-based system. In our proposed work a node set contains one CC and ten TDs. Every node set has two radios which has 128 subcarriers. Following the uplink traffic and the downlink traffic are equal, we just consider the uplink best-effort traffic in the examinations with a specific end goal to facilitate analysis. These nodes frame a hierarchical mesh topology through wireless links and a tree topology through PLC links.

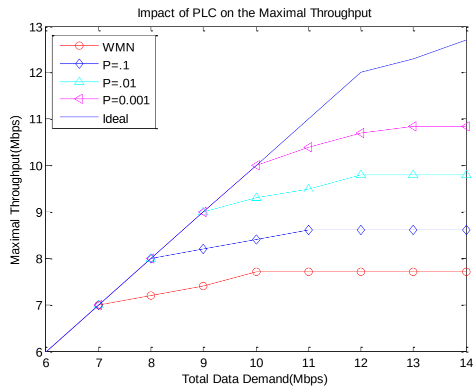

Fig. 2. *Impact of PLC on the maximal throughput*

Figure 2 shows the effect of the PLC system on the maximal throughput. Here we have considered the case that just the WMN is utilized to backing all the VNs. For this situation, the WMN needs to dole out more subcarriers to the real-time services to ensure their reliability requirements. As the rest of best-effort trafffic are less, the troughput will be low. As the WMN is the only network that is utilized, the PLC reliability is sufficiently high to meet all the real-time services' requirements. The blue plane line shows the perfect maximal throughput. Some different cases are additionally tried, in which PLC PER (ϵ_p)(which is stated as P in the graph) shifts from 10^{-1} to 10^{-3}. Lower (ϵ_p) suggests that the PLC can give higher transmission reliability. In this case more subcarriers in the WMN can be utilized for best-effort traffic. The maximal throughput is enhanced through upgrading transmission diversity. The maximal throughput of best-efort traffic is adversely identified with the PLC PER.

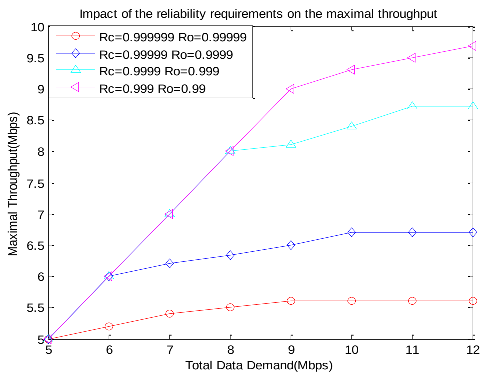

Fig. 3. *Impact of reliability requirements on the maximal throughput*

The allocation of the number of the subcarriers are decided by the reliability required by the real-time services. The higher the real-time service request reliability is, the more subcarriers it expends. The relating maximal throughputs are uncovered in figure 3. It is clear that the expansion of the reliability is at the expense of subcarrier resource consumption. From another point of view, by inserting the real-time VN onto heterogeneous SNs to upgrade the diversity, to a great degree high reliability can be accomplished, which is a troublesome errand in a single SN with lossy link.

Two algorithms are produced in the heuristic solution. algorithm 1 can acquire the maximal throughput, however it doesn't consider fairness. At the point when the overall best-effort traffic demand is 12 Mb/s, the statistical individual satisfied traffic of every node taking into account with Algorithm 1 is shown in figure 4. Under these circumstances, nodes 3 and 6 endure starvation, in spite of the fact that the average satisfied rate accomplishes up to 80%.

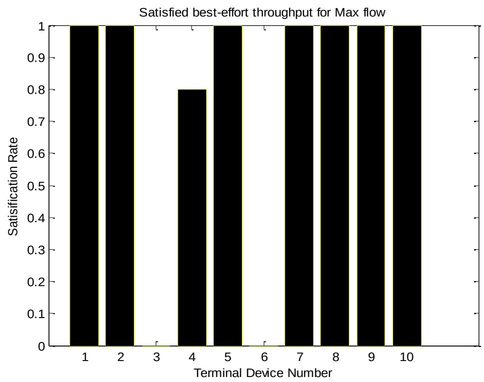

Fig. 4. *Satisfied effort throughput for Max flow*

Algorithm 2 considers max–min fairness while boosting the throughput. It makes nodes exchange a specific proportion of traffic to the CC in a round-robin way. In the experiment, the propotin is set to 1%. With the same input, the aftereffects of Algorithm 2 are appeared in figure 5. From the histogram, it can be realized that no node endures starvation. Moreover, the gap between the maximal and the minimal satisfaction rate is just 1%. The general average satisfaction rate is 78.2%, which is lower than the aftereffect of Algorithm 1 just a bit.

The throughputs acquired by the two algorithms with different traffic demands are looked at in figure 6. The gap between the consequences of the two algorithms is just around 2%. Algorithm 2 enhances fairness drastically at the expense of a little throughput diminish. This element shows that Algorithm 2 is substantially more practical.

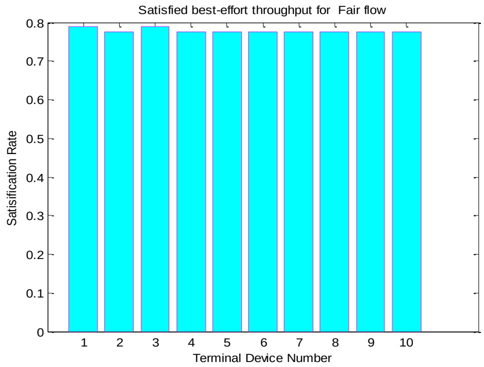

Fig. 5. *Satisfied best-effort throughput for fair flow*

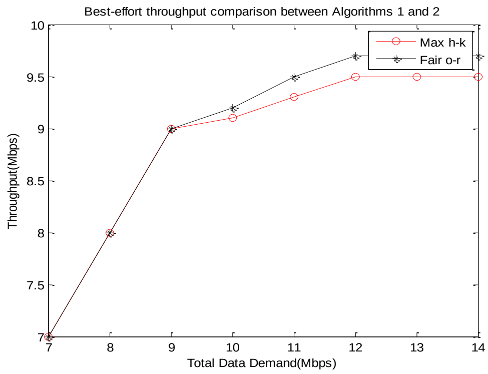

Fig. 6. *Best-effort throughput comparison between Max Flow and Fair Flow*

After applying the data compressing algorithm to the input the maximal throughput we are getting for the same total data demand in the case of Max Flow and Min Flow is as shown in figure 7.

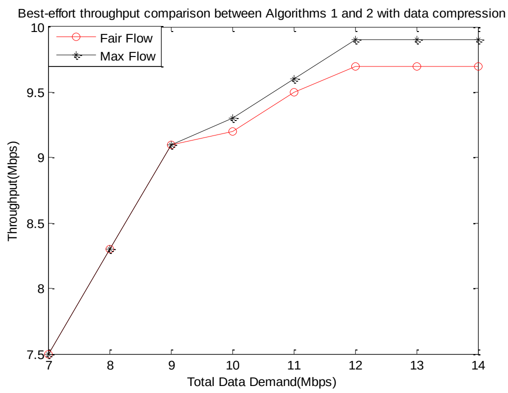

Fig. 7. *Best-effort throughput comparison between Max Flow and Fair Flow with Data Compression*

It is evident here that the best-effort throughput is more in the case of data compression. This is because the data we are giving as the input is compressed. The complexity of the system is reduced with the reduced data at the input, hence, increasing the throughput at the end. Next we summarize presented work.

4 Conclusion

This paper discusses the Network Virtualization technology with a specific end goal to meet different necessities of diverse information systems in smart grid. In the proposed methodology, real-time services were bolstered by VNs. These VNs were mapped to a WMN and PLC network systems. The VNs were isolated under suitable subcarrier assignment, so they could function without mutual interference. Since our problem is considered as NP hard, a heuristic optimization solution was implemented to address this issue and a new algorithm of data compression was applied to increase the system throughput elevate real-time constraints. Experimental computer simulation results show the viability of the proposed approach.

References:

[1] P. Lv, X. Wang, Y. Yang and M.Xu: Network virtualization for Smart Grid Communication, IEEE system journal, Vol. 8, No. 2, June, 2014, pp. 471-482.

[2] I. Akyildiz, X. Wang, and W. Wang: Wireless mesh networks: A survey, Computer Networks, vol. 47, no. 4, Georgia Institute of Technology, Atlanta, USA, March, 2005, pp. 445–487.

[3] S. Galli, A. Scaglione, and Z. Wang: For the grid and through the grid: The role of power line communications in the smart grid, Proceeding of IEEE, vol. 99, no. 6, June, 2011, pp. 998–1027.

[4] N. Chowdhury and R. Boutaba: Network virtualization: State of the art and research challenges, IEEE Communication Magazine, vol. 47, no. 7, July, 2009, pp. 20–26.

[5] N. Chowdhury and R. Boutaba: A survey of network virtualization, Computer Networks, vol. 54, no. 5, April 2010, pp. 862–876.

[6] V. Pothamsetty and S. Malik: Smart grid: Leveraging intelligent communications to transform the power infrastructure, Cisco White Paper, February, 2009, pp. 1-11.

[7] M. Yu, Y. Yi, J. Rexford, and M. Chiang: Rethinking virtual network embedding: Substrate support for path splitting and migration, ACMSIGCOMM Computer Communication, vol. 38, no. 2, April, 2008, pp. 17–29.

[8] Z. Cai, F. Liu, N. Xiao, Q. Liu, and Z. Wang: Virtual network embedding for evolving networks, Proceeding of. IEEE GLOBECOM, 2010, pp. 1–5.

[9] Y. Zhu and M. Ammar: Algorithms for assigning substrate network re-sources to virtual network components, Proceeding of IEEE INFOCOM, vol. 2, 2006, pp. 1–12.

[10] N. Chowdhury, M. Rahman, and R. Boutaba: Virtual network embedding algorithms

with coordinated node and link mapping, Proceeding of IEEE INFOCOM, vol. 20, no. 1, February, 2012, pp. 206-219.
[11] J. Lischka and H. Karl: A virtual network mapping algorithm based on subgraph isomorphism detection, in Proceeding 1st ACM Workshop Virtualized Infrastructure System Architect, 2009, pp. 81–88.
[12] I. Houidi, W. Louati, W. Ben Ameur, and D. Zeghlache: Virtual network provisioning across multiple substrate networks, Computer Networks, vol. 55, no. 4, March, 2011, pp. 1011–1023.
[13] M. Schwartz: Carrier-wave telephony over power lines: Early history [history of communications], IEEE Communication Magazine, vol. 47, no. 1, January, 2009, pp. 14–18.
[14] K. Dostert: Power line Communications, Englewood Cliffs, NJ, USA: Prentice-Hall, 2001.
[15] H. Ferreira, L. Lampe, J. Newbury, and T. Swart: Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines, Hoboken, NJ, USA: Wiley, 2010.
[16] B. Lichtensteiger, B. Bjelajac, C. Müller, and C. Wietfeld: RF mesh systems for smart metering: System architecture and performance, in Proceeding 1st IEEE Int. Conf. SmartGridComm, 2010, pp. 379–384.
[17] IEEE Standard for Broadband over Power Line Networks: Medium Ac-cess Control and Physical Layer Specifications, IEEE Std., 2010, pp. 1901-2010.
[18] G. Bianchi: Performance analysis of the IEEE 802.11 distributed coordination function," IEEE J. Sel. Areas Commuication, vol. 18, no. 3, March, 2000, pp. 535–547.
[19] J. Zhu, A. Waltho, X. Yang, and X. Guo: Multi-radio coexistence: Challenges and opportunities, in Proceeding IEEE ICCCN, 2007, pp. 358–364.
[20] A. Dhananjay, H. Zhang, J. Li, and L. Subramanian: Practical, distributed channel assignment and routing in dual-radio mesh networks, ACM SIG-COMM Comput. Commun. Rev., vol. 39, no. 4, October, 2009, pp. 99–110.