Research Article

Scalability Dynamic Multicast Labels Management Mechanism for Ubiquitous Data-Centric Sensor Networks

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The significant difference between traditional electric power system and smart grid is the cooperative control of power flows and information flows. With a large number of secondary equipments accessed into smart grid, the electric power communication network becomes one type of ubiquitous data-centric sensor networks. Real-time and reliable multicast services are required for power system's stable operation. Multiple Protocols Label Switching (MPLS) with its traffic engineering capabilities has emerged as a powerful tool to provide QoS support in backbone transmission networks. But previous MPLS unicast and multicast protocols have common disadvantages, not scalable enough, especially for various intelligent electronic devices following distributed generators frequently accessed into smart grid. To overcome the problems of overfull labels consuming bandwidth and prolonging delay, this paper proposed a novel labels dispatching mechanism based on Resource ReSerVation Protocol (RSVP) and message injecting and headward impelling technologies. Based on a set of accurate mathematical analyses and simulation experiments in a typical distributed power system scenario, the new mechanism could effectively reduce the total number of labels and overheads, save bandwidth, and shorten the multicast tree establishing time. The good scalability can adapt much better to ubiquitous and thick electrical advanced metering application.

1. Introduction

Energy shortage and environmental pollution become one of the global issues. To achieve the low-carbon and highly security power supply, “Smart Grid” and “Distributed Generation” are deeply researched [1, 2]. With Intelligent Electronic Devices (IED), smart computing algorithms, Advanced Metering Infrastructure (AMI), and communication techniques, traditional electric power systems have gradually transformed into highly efficient and reliable intelligent power grid—smart grid [3].

In smart grid, a great number of secondary equipments are accessed into the system with wire and wireless communication techniques and become one special electric power communication network [4, 5]. This system, which realized the advance metering, data transmitting, and information processing, is one type of ubiquitous data-centric sensor networks [6–8]. Different types of metering electrical information in the network are gathered to Modern Dispatching Center (MDC); at the same time, control instructions from MDC, computed based on metering electrical parameters, are transmitted to actuators. Real-time and reliable multicast protocols to achieve various QoS requirements are the basic guarantee for power system's stable operation. Multiple Protocols Label Switching (MPLS) standard [9], framed by IETF (Internet Engineering Task Force), can achieve rapidly routing and guarantee multiply QoS requirements. It has become one of top choice technologies applying in electrical power digital transmission network [10, 11]. However, with the utilization of distributed generators, such as wind generator, photovoltaic generator, and biomass power generation, many metering instruments should be used to measure instantaneous voltage $u(t)$, current $i(t)$, and power $\{P, Q\}$ [12], in which instruments are regarded as data nodes and accessed into the core transmission networks, called “last mile” access networks. Data nodes’ frequent access and quit need effective dynamic multicast mechanism to adapt both MPLS core network and access network.

Dynamic multicast, as the special type of multicast, allows any member to access or leave the current multicast cluster,
which is more complex than static multicast [13]. The core technologies in dynamic multicast include the label switching promotion model, signaling selection, and multicast tree structure. This paper analyzed the previous multicast labels dispatching mechanisms and proposed a novel labels dispatching mechanism based on RSVP (Resource ReSerVa
tion Protocol). The new mechanism with message injecting and headward impelling technology can effectively save the utilized labels and bandwidth and reduce the multicast tree establishing time.

The remainder of this paper is organized as follows: Section 2 presents the related works, including MPLS, unicast LDP protocol, and MPLS multicast; Section 3 explains message injecting and headward impelling technology in detail; a set of accurate mathematical analyses is described in Section 4, and the number of labels and control packets utilized in multicast are quantitatively calculated; Section 5 presents our evaluation through simulation, followed by conclusion in Section 6.

2. Analysis of Related Issue

MPLS is a special technology to map layer 3 traffic onto layer 2 delivery, with which faster forwarding is done at layer 2 with an "exact match" search compared to the traditional "longest prefix match" search of layer 3 routing. MPLS is also a traffic engineering protocol. QoS is provided by associating packets with Forward Equivalence Class (FEC), which in turn can get preferential treatment. This association is done at the ingress Label Switching Router (LSR), which initiates the Label Switched Paths (LSP) setup, and once the LSP is in place the intermediate LSRs switch according to layer 2 forwarding. Because it can effectively support fast and guarantee QoS service communication, MPLS has now become one of the best technologies for backbone IP network [9, 14].

2.2. Multicast Protocols in MPLS. The inherent Label Distribution Protocol (LDP) of MPLS in RFC 3209 is restricted to unicast label switched paths, which does not fit for multicast. Multicast is a point-to-multipoint or multipoint-to-
multipoint communication mode.

In multicast services, a single transmission is needed for sending a packet to \( n \) destinations, while this transmitting should be required to seamlessly extend QoS guarantees. In the extreme case, dynamic multicast routing can be regarded as a series of static heuristic algorithms to recalculate multicast tree in each period of multicast membership change. Several multicasts protocols were suggested to reach a minimal end-to-end delay, limited jitter, and efficient use of bandwidth, which included spanning join protocol (SJP), QoS-aware multicast routing protocol (QMRP), and QoS sensitive multicast Internet protocol (QoSMIC) [18]. These protocols are known to be multiple path routing protocols which determine several paths towards the multicast tree. It is obvious that frequently operating heuristic algorithm will prolong calculation time and induce high loss packets rate during the multicast tree reconstruction. And it also produces a higher network overload that is introduced in order to accommodate the multipath resource reservation.

The major disadvantage of the existing multicast protocols is that they are not scalable enough for large-scale networks, especially for ubiquitous data-centric sensor
network. Multicast suffers from scalability problem with the number of concurrently active multicast groups because it requires a router to keep forwarding state for every multicast tree passing through it, and the number of forwarding states grows with the number of groups. Scalability can be evaluated not only in terms of the overhead growth in the presence of a large number of groups but also by the number of participants per group and by groups for which the set of participants changes often over time. Overhead can be measured in terms of memory resources (in routers) as they relate to routing states maintained per group and can be measured also by bandwidth resources in terms of control or signaling messages per group and also by processing power [19]. Therefore, a multicast routing protocol should be simple to implement, have the scalable and robust capabilities, use minimal network overhead, consume minimal memory resources, and interoperate with other multicast routing protocols. Moreover, if one multicast routing algorithm will be applied in electrical power digital transmission networks, it should also be able to keep the smallest changes with low cost and oscillation time in each updating event, such as distributed generators’ access and quit.

3. Message Injecting and Headward Impelling Technology in Dynamic Multicast

The above analysis shows that multicast tree creating process is different from the unicast LSP creating process in MPLS. If the traditional message-flows dispatching label distribution mechanism is adopted, the upstream LSR needs to send Label-Request messages to each output interface connecting oriented downstream LSRs, whenever a new member request to access. Each downstream LSR also needs to reply a Label-Request message. Because those response messages are independent, the same type of FEC probably has different bindings in the reply labels. The upstream LSR must traverse all of the access requests. If the multicast tree is a multilayer structure, label messages will power series increase and the established time of the Label Switched Path (LSP) will be exponentially prolonged, all of which destroy the networks’ dynamic and scalability.

This paper proposed a novel label distribution mechanism to support dynamic multicast in the ubiquitous data-centric sensor network applying electric power system. For each member requesting to join multicast cluster, the new mechanism can effectively restrict the labels’ distribution for each similar FEC mark, and less labels will also reduce the LSP’s establish time. In this dynamic multicast algorithm, a new Message injecting and Headward impelling (MiHi) technology is designed.

3.1. Networks Model. Based on IEC 61850, second equipments can be connected into SCADA as logic nodes [20, 21]. A whole smart grid communication subnet, operating information flow, can be abstracted as a graph, which is established by thousands of different logical nodes/routers and edges. Each node has its own properties and exchanges data with its neighbor. Finally, a connected, simple digraph

\[ G = (V, E, M) \]

is established, where \( V \) is the set of logic vertex, \( E \) is the set of edges, and \( M = \{ H_{ij}, H_{kj} \} \) is the set of attributes. Here, \( H_{ij} \) is the set of each vertex’s measurements and \( H_{kj} \) is the set of each edge’s measurements.

For each vertex, \( H_{ij} = \{ \text{Color}[k], \text{Delay}_{\text{max}}[k] \} : \text{Color}[k] \) is the multiree nameplate for each vertex \( i \), which means that \( v_j \) belongs to multicast tree \( Tm_j \). Because different multicast trees can include the same vertex, the measurement \( \text{Color}[k] \) is one array. Date from the same multicast tree \( Tm_j \) can be aggregated effectively; otherwise data will just be transmitted overhead; \( \text{Delay}_{\text{max}}[k] \) is the delay on the corresponding router (the sum of queuing delay, transmission delay, and propagation delay). In each edge \( H_{kj} = \{ \text{EnBW}_k, \text{Metric}_k \} : \text{EnBW}_k \) is the maximum bandwidth provided for applications; \( \text{Metric}_k \) is the reserved measurement defined by electric power operation.

Based on the mathematic model, the multicast tree satisfying QoS requirements can be selected from dispatching center to special second equipments or sensors.

3.2. MiHi Technology. Based on the above network model, a novel MiHi technology is proposed to support dynamic multicast in the ubiquitous data-centric sensor network. When a new IED should join one of multicast tree, a special request packet is generated by the IED. MiHi embedded this packet into an agent, and reversing impels it to the root of multicast tree, that is, MDC. Because RSVP technology is used during the agent routing, the established LSP from the new joined IED to MDC has reserved communication resource to satisfy the QoS requirements in the traffic FEC. Therefore, a new member accessed and the transmission tunnel established processing is finished at the same time, which reduced the LSP’s established time and effectively restricted the labels’ distribution for each similar FEC mark.

The details of MiHi and the LSP established processing are presented as follows.

Without loss of generality, assume that there are \( k \) number of multicast groups in the network; each group is a multicast tree structure. \( k \) number of multicast trees are shown as \( Tm_1, Tm_2, \ldots, Tm_k \). When a new IED \( v_j \) is applied to join the existing multicast group \( Tm_j \) at time \( t \), \( v_j \) should send a multicast joining request message \( \text{ARP}(v_j, \text{FEC}_j, Tm_j) \) firstly.

Secondly, message \( \text{ARP}(v_j, \text{FEC}_j, Tm_j) \) will be embedded into a master mobile agent \( \text{MA}_m(\text{FEC}_j, Tm_j) \). \( \text{FEC}_j \) and \( Tm_j \) will be copied from ARP field to MA field, which will be used during agent migration. The format of \( \text{MA}_m \) is shown in Figure 2.

Mobile agent then travels following the optimized direction, till reach any one of members’ LSR, belonged to multicast tree \( Tm_j \). If there are equivalent paths at one relay router, \( \text{MA}_m \) will generate several slave agents and send them to the different output ports to realize the parallel routing. The mobile agents’ master-slave pattern is shown in Figure 3.

Based on the FEC information mapping from ARP field to MA field, LSR assigns the Output Label (OL) and Out Interface (OIF) for the forthcoming multicast flow. One OL can be shared and reused with original labels in the same multicast group; OIF is the multicast flow transmission
interface and the ARP's input interface. The defined OL and OIF are added to the LSR’s Label Switching Table (LST). The format of LST is presented in Figure 4.

LSRj replied message APPj from OIF, in which the message’s living time TTL is initialized. Each relay LSR checked the routing requests in APPj and appraised the interface resource to decide whether there is enough resource for this type of flow or not. If there is enough resource, OL will be pushed into the LST and then forward APPj to the next hop router till νj. If the reservation request is refused, the LSR will send error to two opposite directions: νj and MDC. The relay LSRj should remove corresponding OL from LST.

4. Mathematical Analysis of MiHi Mechanism’s Effectivity

We calculated the number of used labels during new members access and compared the MiHi mechanism with the traditional flow trigger label assignment mechanism.

Assume that the number of MPLS multicast tasks is s and the distance between the access point of multicast tree and the applying dynamic join member LSR is h hops. Each relay LSR’s idle output port number ki (i = 1, 2, ..., m) is mutually independent and follows a normal distribution N(μ, σ²), μ ≫ 1. Using Chebyshev’s law of large numbers, the following equation can be got:

∀ε > 0,

\[ \lim_{n \to \infty} P \left\{ \left| K_n - \mu \right| < \varepsilon \right\} = \lim_{n \to \infty} P \left\{ \left| \frac{1}{n} \sum_{i=1}^{n} k_i - \mu \right| < \varepsilon \right\} = 1. \]  

(1)

Equation (1) shows that when n is a large number the arithmetic mean \( K_n \) of the random variable \( k_i \) (i = 1, 2, ...) is close to its mathematical expectation \( E(k_i) = \mu_0 \) (i = 1, 2, ..., m). So, based on traditional flow trigger label assignment mechanism, implying one time of a new member’s access procedure, the require labels’ number is

\[ \text{Label} = s \times K_n \times h = s \times \mu \times h. \]  

(2)

The number of control packets is

\[ \text{Packet} = \text{Label} = s \times \mu \times h. \]  

(3)

We also calculated the number of labels in the processing of MiHi mechanism. Because the require came from downstream, only one determinate path from new joining member to access point need assign and delivery labels, in which the number of labels is

\[ \text{Label} = s \times h. \]  

(4)

Adding the control packets for resource reversion to ensure that the path satisfies QoS requirements, the total number of control packets is

\[ \text{Packet} = s \times 2h. \]  

(5)
Compared with the number of labels and control packets in (2)–(5), because of $\mu \gg 1$, MiHi mechanism can effectively constrain the number of labels and control packets. If the scale of multicast cluster is large and the multicast joining requirements are frequent, much more labels and overheads are saved by MiHi, and the decrease of bandwidth and multicast access time can improve the network's transmission performance.

5. MiHi Mechanism Performance Evaluation

A typical distributed power system, shown in Figure 5, is employed in the simulation, in which the multicast communication network is marked as blue dotted line. There are three original multicast groups $T_{m1}$, $T_{m2}$, and $T_{m3}$. $T_{m1}$ is the switch control group, in which the traffic is switch signals; $T_{m2}$ is made up with electronic sensors, which measure gas turbines and accumulators' electrical power information; three sets of current/voltage transformers are connected to the $T_{m3}$ group, metering feeders A, B, and C current $i(t)$, and voltage $u(t)$. Now, a 30 KW wind turbine generator and several loads will be connected on feeder B, accessed into the power system. The electronic sensors and switch control devices should be synchronously accessed into multicast groups.

Based on the traditional flow trigger label assign mechanism (FTLa), MDC should assign labels to each idle output port and push labels into LST. Then these labels were sent to each corresponding port and transmitted to downstream LSR till the access point to correspond multicast group. Each time one of the relay LSRs received a new FEC label, it should create a new label switching item and push it into LST. It means that, during the member joining processing, a great number of labels for the same FEC and label switching items were created, but only the label reaching the access point is valid. Other invalid labels should keep in each relay routers’ LST, not deleted until $AT = 0$.

MiHi mechanism is initiated from the joining member with sending the request message ARP. ARP is pushed to
the multicast tree access point or MDC. So each relay router needs only to assign a single label for the same type of FEC and establishes LSP with resource reservation. Figure 6 shows the relation curve of new multicast member and required labels. In the figure, with the increase of requesting access hosts number, the performance of MiHi is better than flow trigger label assign mechanism. The growth rate of utilized labels by FTLa accords with quadratic function:

$$y(n) = 0.90n^2 - 1.74n + 3.04, \quad n > 0, \quad (R^2 = 0.9869).$$

Here $R^2$ is correlation coefficient.

But the correlation of labels increases the rate and the number of join hosts is linear by MiHi mechanism; the fitting curve is

$$y(n) = 1.98n + 0.55, \quad n > 0, \quad (R^2 = 0.9976).$$

Therefore, MiHi mechanism effectively constrains the used labels and can fit for the large scale of multicast application, which guarantees the MiHi mechanism's scalability.

Multicast transmission paths’ creating time determines whether measurement signals from electrical meters can be real time uploaded to MDC, and control signals can reach IED without long delay. Therefore, short LSP setup time is one of the key indicators to improve the smart grid performance. If the bandwidth is constant, the key factors affecting LSP creating time are multicast tree depth, number of nodes in the multicast tree, and the transmitting packet loss rate. The greater the layer of multicast tree, the more the number of nodes, and the higher the packets loss rate, the longer the LSP creating time. Here we set a scene with two different link data packets loss rates ($\text{Plr} = 0$ and $\text{Plr} = 0.05$) and dynamically increase the multicast tree layers to detect LSP creating time. The results are shown in Figure 7. In the figure, with the increase of packets loss rate, LSP creating time with flow trigger label assign mechanism significantly prolong. But MiHi mechanism well inhibits this upward trend. MiHi has better adaptability to changing complex and volatile network environments.

Figure 8 depicts overhead packets in different multicast tree depths. The same tow scenes with $\text{Plr} = 0$ and $\text{Plr} = 0.05$ packets loss rate are set in the experiments. In the lightweight multicast group, the utilized overhead packets by FTLa are less than MiHi, because MiHi employed resource reversion mechanism to ensure that the path satisfies QoS requirements, which will consume almost double control packets. But with the increase of multicast group's scale, the number of relay LSR’s idle output port number $K$ expands. Much more overheads carrying mobile agents are assigned to each of the idle output ports by FTLa mechanism. In addition to the probability of packets loss, great number of overhead to are utilized ($\text{No. overhead}_\text{FTLa} = 136$, compared with $\text{No. overhead}_\text{MiHi} = 60$), which also consumed much more bandwidth. This experiment shows that MiHi can adapt much better to ubiquitous and thick electrical advanced metering scenario.

6. Conclusion

MPLS has been widely used in electrical power digital communication backbone network. WSN including various...
electronic sensors and IEDs is the main technology to realize the “last mile” access network. How to better support multicast service in this kind of hybrid network to control distributed energy grid’s information flow has become one of the hotspots. Traditional multicast protocols used input flow control trigger label assign mode. The upstream LSR intercepted input control messages from the downstream LSRs and then sent labels binding requests to downstream through LSPs. Because the upstream LSR pushed labels binding requests, more than one OL should be assigned for each output port of LSRs. While multicast tree level and multicast members expand, a great number of invalid labels would congest each LSR’s label switching table and communication bandwidth. It is a fatal problem to destroy the MPLS multicast scalability.

To solve the above problems, this paper proposed a novel message injecting and headward impelling technology to effectively constrain labels’ flood. When the downstream LSR sends control messages to upstream LSR, it also intercepts output control messages and then triggers LDP to send label binding request to upstream. OL is only assigned to the multicast join members, so it can effectively control the amount of traffic when new members access the system and improve MPLS scalability during dynamic multicast. Using a typical distributed power system in experimental simulation, we measured the performance of MiHi and compared it with the traditional flow trigger label assign mechanism. Results were very promising and showed that the performance of our novel labels assign mechanism is much better than others in constraining the utilized labels, as well as in reducing new member access time. The results present that MiHi has good scalability and adaptability for applying the distributed generation combined to the smart grid.

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