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“A Novel Routing Control Method Using Federated Learning in Large-Scale Wireless Networks”

In the 2010s, cellular phones were introduced with the 4th Generation (4G) Wireless communication standard. This protocol supported even faster data speeds and better coverage than the previous 3G Wireless standard. The 2020s have started introducing 5th Generation (5G) Wireless which prides itself on even faster speeds, reliability, larger capacity, reduced latency, and a new feature, simultaneous connections. 5G still runs on the previous standard Gigahertz band which is not compatible with the proposed future standard protocol Beyond 5th Generation (B5G) that includes the 6th Generation standard. 5G has not caught massive appeal due to lackluster cellular coverage and its range. IEEE Spectrum notes that 5G uses high-frequency millimeter waves which are more prone to physical interference including through solid walls. Researchers have proposed wireless mesh networks to be the new standard for B5G protocols. Wireless Mesh Networks (WMNs) consist of source and destination routers that securely set up bidirectional communication paths where data needs to be sent. These routers are expected to replace massive cellular towers due to their low cost and density. Wireless Mesh Networks however are deficient in path traversal due to the ever-changing size of routes data travels to. Traditional routes are specifically for wired networks and could not be adapted if used in wireless networks.

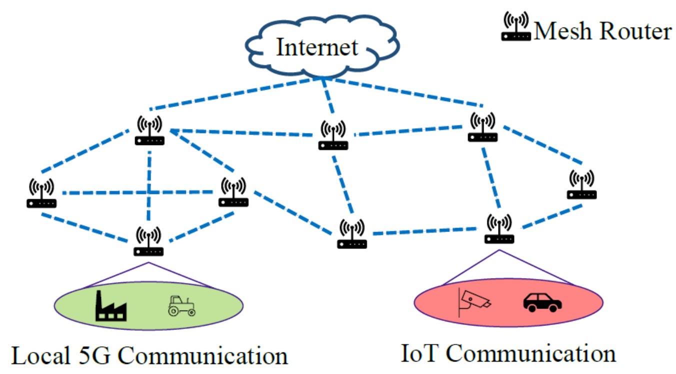

Fig. 1. Overview of the Wireless mesh network.

Researchers Nei Kato, Yuichi Kawamoto, and Yoshihiko Watanabe of Tohoku University devised a routing algorithm for WMNs powered by federated learning, a form of machine learning, in their paper "A Novel Routing Control Method Using Federated Learning in Large-Scale Wireless Mesh Networks" published in the journal IEEE Transactions on Wireless Communications on April 28th, 2023, by IEEE. The core idea shown in this paper is that route analysis by a global machine learning model trained by federated learning in a large-scale wireless mesh network can result in congestion being avoided and a decrease in E2E delay and packet-loss ratio compared to alternative routing protocols. Congestion appears when too many packets are at a specific node which leads to some being deleted resulting in delays. The global model would predict if congestion would occur in the future and if so, it would choose another route for network data to go through.

Some methods have tried to address wireless mesh network routing protocols; one routinely updates new optimal routing tables whenever nodes are added or removed but does not consider network reliability due to increased congestion. One Software Define Networking (SDN) architecture utilizes a hybridization of Optimized Link State Routing with OpenFlow and IP Routing and is superior to other SDN methods but is insufficient in node compatibility. Open

Shortest Path First (OSPF) routing involves looking at maximum data speed via the connection status of available routers instead of calculating the lowest number of intermediary routers. OSPF is not scalable to large-scale WMNs due to shifts in network topology by physical path interference which results in more computing power needed to reroute data. Large-scale WMN routing was looked at, but these did not consider Internet congestion or LTE coverage. Routing powered by machine learning has been examined including dynamic routing control in small WNMs, as shown in the paper “On Removing Routing Protocol from Future Wireless Networks: A Real-time Deep Learning Approach for Intelligent Traffic Control” by authors F. Tang et al., but this is not scalable to large WNMs. The researchers noted that machine learning takes a long time to process (especially for instant communication), takes up network resources, and is difficult to implement when node sizes are ever-changing. However, it can dynamically optimize should routers go down or congestion occurs. The researchers note, “It is necessary to develop a machine-learning method that can rapidly learn with fewer computational resources” (Kato, Kawamoto, Watanabe). Distance, path vector, and other machine learning techniques were not studied as the wireless communications in this study were performed with millimeter waves.

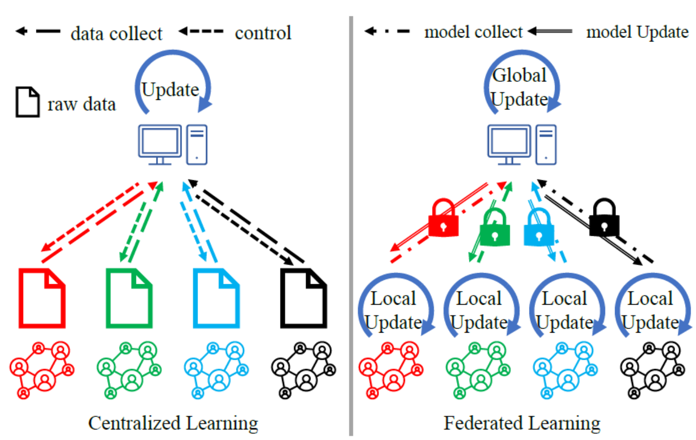

Fig. 2. The comparison of centralized learning and federal learning.

The research group utilized federated learning, which involved many computers hosting local machine learning models of a small size being used to individually train based on different datasets that eventually would train the global model. Each computer runs a local model which has training data that is independent and identically distributed. It was found that more computers led to a better global federated learning model, and it was decided that raw data was not given to other local models to preserve data confidentiality. These local models are then fed into a global model for analysis. Through these means, the problems with computation slowness and intensity were mitigated with federated learning. This model was fed through a convolutional neural network (CNN) which uses convolution, pooling, and fully connected layers through its algorithmic process. This was favored over a traditional neural network as CNN can work with multidimensional data without changing the inputs and result in a vast array of directional relationships. The federated learning model is fed by the number of packets on standby in a buffer, end-to-end (E2E) delay, packet loss, and the number of packets created by the nodes for routing input data. Each route was analyzed with federated learning and the CNN to predict and avoid future congestion. This method ensured that learning was the most efficient and effective way for the routes to be determined.

Ninety-one mesh routers were utilized to overcome minimal interference and high-distance attenuation. The federated learning sector was structured with 3x3 nodes with each node having a communication channel with one surrounding node. The whole network had 3x3 areas with a connection via communication channels with neighboring areas. Each packet's length and delivery times were identical to each other and communication channels to other regions were assumed to be ideal with zero delay and infinite capacity. Packets between areas are not held in the standby buffer and are directed to the next region. Congestion is defined as the average interregional E2E packet-loss ratio and interregional E2E delay for all routes is greater than their average values. These routes cover the two nodes that the route covers and the route itself. Two sets of global modeling from one hundred training cycles were performed with each area where routes go through having one global modeling set. Parallelization allowed nine areas with nine hundred training iterations. Online learning was preferred to consolidate local models into global ones while offline has only local models. An area had a routing computer that did local learning. Due to the global model obtaining data from local models, local computer resources were assumed to be not demanding. Calculations involved setting the quantity of transmitted packets to 4 Gbps as multiple people can communicate from the same router. The required buffer size *M* is calculated from the throughput mu and the round-trip time. The average E2E packet-loss ratio and average E2E delay of the OSPF method, and the proposed and conventional methods were compared with evolution parameters. These statistics are then compared to results that occurred if the average packet generation rate was based on the evaluation parameters. Lastly, statistics were compared to those when channel capacity between nodes is dependent on the evaluation parameters.

Numerical analysis was measured on how effective the path-control method is based on machine, federated learning, and evaluated the model's ability to detour around congestion. Measurements were also made on how many transmitted packets and communication path capacity differences. A successful proposal will have congestion avoided and the packet-loss ratio and E2E delay will decrease compared to OSPF. The new proposed method had a better buffer-wait delay and a better E2E average packet-loss ratio as it detours from routes that can lose packets. The proposed method is better even as the average packet generation rate changes. The average E2E packet-loss ratio improved by approximately 5 Gbps for transmitted packets as the study utilized big packets that are bigger than the 20 Gbit capacity of the channel nodes. 8 Gbps speeds were improved for average E2E delay and average E2E packet-loss ratio as congestion was lessened. No matter the quantity of packets or the internode channel capacity, the proposed method is shown to be much more efficient. When internode channel capacity is about 15 Gbps, there is almost zero packet-loss ratio as the maximum value used to calculate the average packet size of 4GBps is about 15 Gbit per unit time. This also happens with the OSPF method as an increase in internode communication-channel capacity reduces congestion in the middle area. The new method is more resilient than the other methods.

The authors only mention that the local federated learning models did not use each other’s data due to the nature of how the local models learned; only the models' configuration was exchanged. It is also inferred from Figure 2 that federated learning is secure at least from the data perspective. The paper does not specifically indicate any security concerns related to the unique routing method. Unauthorized access and eavesdropping, via man-in-the-middle attacks, can occur if the machine learning model is not secured with strong encryption and key management which ensures data confidentiality in the routing protocol. Appropriate authentication should also be needed so no adversary would be able to hijack the model or tinker with the datasets training the local federated learning models. Signal jamming can also occur to cause severed connections between routers leading to more computation power and direction being provided by the global machine learning model.

Potential applications include the fact that wireless mesh networks are vying to be the standard for 6th Generation Wireless Communications. Even if they are not considered, wireless mesh networks can be used in a wide range of applications. Municipal Wi-Fi networks are being run on wireless mesh networks to allow for maximum performance and minimum downtime.

WMNs are also being used in disaster recovery sites which allows for multiple nodes to be added or removed from the network at ease especially since the environment may lead to nodes being disconnected from each other. The top speed of WMNs also allows for data to flow and exchange between various devices in the disaster site. Industrial Internet of Things (IoT) devices also can take advantage of wireless mesh networks due to their necessity to ensure that all the components of a system are working. This is supported by the quick exchange of data between sensors, embedded chips, machines, and control systems computers to determine if a machine needs maintenance. It also allows industries to cut the cord and have their devices go fully wireless in terms of data communication. Should the network recognize a slow transfer of data in a route between some devices, it can plan another route in the network to allow the data to flow optimally.

Future opportunities were considered by the researchers who noted that packet types and network topology need to be studied further as alternative routes presented in the study are generalized. Say a large packet is being sent around the network. This can cause slower delivery times for a packet coming in the opposite direction as the larger packet is hogging the bandwidth from the other direction's route on the same connection line. Different devices may also cause variations in how the wireless mesh network sends and receives data. Packets that come from all sorts of places and directions can be assessed with new machine-learning routing algorithms that delve into way more complex routing possibilities and which can oversee complex environments with several types of congestion to ensure robustness and fast delivery of data. Doing so will enable ever-changing networks with solid communication services, especially in real-world situations like industrial factories. Wireless mesh networks will allow industrial plants to be ever more synchronized and up-to-date with each other. This will allow for the most efficient creation of products and goods that will lead to an uptick in the global economy.

Works Cited

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