Adaptive Transmission Optimization in SDN-Based Industrial Internet of Things With Edge Computing

Xiaomin Li, Di Li, Jiafu Wan, *Member, IEEE*, Chengliang Liu, and Muhammad Imran

***Abstract*—In recent years, smart factory in the context of Industry 4.0 and industrial Internet of Things (IIoT) has become a hot topic for both academia and industry. In IIoT system, there is an increasing requirement for exchange of data with different delay flows among different smart devices. However, there are few studies on this topic. To overcome the limitations of traditional methods and address the problem, we seriously consider the incorporation of global centralized software defined network (SDN) and edge computing (EC) in IIoT with EC. We propose the adaptive transmission architecture with SDN and EC for IIoT. Then, according to data streams with different latency constrains, the requirements can be divided into two groups: 1) ordinary and 2) emergent stream. In the low-deadline situation, a coarse-grained transmission path algorithm provided by finding all paths that meet the time constrains in hierarchical Internet of Things (IoT). After that, by employing the path difference degree (PDD), an optimum routing path is selected considering the aggregation of time deadline, traffic load balances, and energy consumption. In the high-deadline situation, if the coarse-grained strategy is beyond the situation, a fine-grained scheme is adopted to establish an effective transmission path by an adaptive power method for getting low latency. Finally, the performance of proposed strategy is evaluated by simulation. The results demonstrate that the proposed scheme outperforms the related methods in terms of average time delay, goodput, throughput, PDD, and download time. Thus, the proposed method provides better solution for IIoT data transmission.**

***Index Terms*—Adaptive routing, edge computing (EC), industrial Internet of Things (IIoT), software-defined network.**

I. Introduction

DUE TO the recent advancement in industrial wireless networks (IWNs) [1], [2], Internet of Things (IoT) [3], [4], artificial intelligence [5], [6], industrial big data [7], [8], and some other information and communication technologies, both smart factory and Industry 4.0 have gradually developed. The smart manufacturing lines and system increasingly exchange large amounts of data from different devices, machines, managements, and users [9]–[12]. The information communication and network of different features data flows play the basic and critical role in this complicated system. Therefore, the design and implementation of highly efficient, flexible, and adaptive communication systems are essential for smart factories and Industry 4.0.

IoT as an effective communication framework, is gradually adopted in industrial scene and industrial IoT (IIoT) [24], [25]. Moreover, the current research developments, such as clustered or grouped IWNs [13]–[15], software defined network (SDN) [16], [17], [42], cloud and edge computing (EC) [18], [19], and multipath transmission protocol [20], [21], have provided a preliminary basis and enabled the design of high-performance and adaptive system for IIoT. However, there are some differences between traditional IoT and IIoT. As shown in Fig. 1, there is an obvious difference between traditional [Fig. 1(a)] and IIoT [Fig. 1(b)]. The ever-growing studies on IoT and wireless networks show that clustered or group network has some distinct advantages in terms of extendibility, flexibility, and centralized management [26]. So, the hierarchical structure is widely adopted in IIoT. In additional, the quality of service of IIoT is different from IoT. The IIoT emphasizes the real time and reliability comparing to the IoT throughput and packet loss rate.

On the other hand, due to big data and machine to machine (M2M) communication the requirements on industrial application are increasingly growing [22], [23], and new trends are progressively aggravating the communication traffic of IIoT and data transmission. Meanwhile, due to the continuous expand of network scale, different data flows emerge into industrial application and smart factories. Although many studies focus on this topic, it is obvious that these commendable attempts do not consider characteristics and architecture of IIoT. In the traditional IoT framework, the routing path between two devices is not changed because of an unoptimizable traffic path. Therefore, the traditional data transmission methods do not meet actual IIoT requirements.

Although some preliminary works have been focused on adaptive transmissions, performance optimizations in wireless network, these methods are not considered the big data communication requirements, industrial network properties, and network topology. As discussed above, there are some new

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X. Li, D. Li, and J. Wan are with the School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510006, China (e-mail: xiaocao0624@163.com; jiafuwan_76@163.com; itdili@scut.edu.cn).

C. Liu is with the School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200000, China (e-mail: chlliu@sjtu.edu.cn).

M. Imran is with Computer Science Department, King Saud University, Riyadh 11692, Saudi Arabia (e-mail: cimran@ksu.edu.sa).

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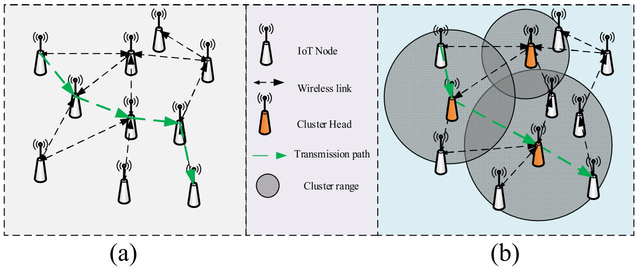

Fig. 1. Framework of (a) traditional and (b) IIoT.

major challenges related to the IIoT data transmission. The motivations behind this paper are based on the following observations. First, current network framework is gradually becoming unsuitable to the new challenges. So, a novel effective architecture must be proposed to deal with a large amount of data traffic with different level among devices. Second, there are centralized routing algorithms or transmission methods based on clustered IoT, which are unable to address different delay levels data streams and online fast decision requirements of IIoT. Therefore, enhanced data transmission methods should be proposed based on new network architecture, such as SDN and EC. Third, although a decent number of studies on optimization routing path are given by employing the backbone network and heuristic algorithms, the traffic congestion in backbone mostly used nodes along with energy consumption unbalance situation are not thoroughly investigated.

In this paper, an adaptive transmission architecture and approach with SDN and EC for IIoT is proposed. In this paper, a clustered data transmission framework is adopted in the proposed algorithms with SDN and EC. The optimization has the potential to significantly improve the performance of IIoT in light of SDN and EC techniques. The contributions of this paper are in the following threefold.

1) An SDN-driven architecture for IIoT is proposed in the context of EC to facilitate the management of limited communication resources. Current clustered network system focuses on the centralized management and does not deal with the real-time decision, separation of data flow (specially control and data flows) and quality of services (QoS) of M2M communication.
2) A highly adaptive and effective transmission routing mechanism is introduced. To adapt data flows with different time consumption demands, an optimum routing is selected from the candidate path set by employing the path difference degree (PDD). In order to deal with the urgent data flow, an adaptive power control strategy is presented to create a highly effective path.
3) In order to evaluate the proposed scheme, a simulation is conducted. The results demonstrate that proposed scheme outperforms the conventional schemes in terms of average delay, goodput, throughput, PDD, and throughput, thereby, providing better solution for adaptive data transmission in IIoT.

This paper is organized as follows. The related works are presented in Section II. The IIoT framework with SDN and EC is introduced in Section III. In Section IV, an adaptive data transmission algorithm is proposed. The simulation results are discussed in Section V. Lastly, a brief conclusion is given in Section VI.

II. Related Works

This section briefly outlines existing efforts regarding to this paper topic. The related works can be categorized into three groups: 1) studies on data transmission path (DTP) in IoT; 2) studies on SDN for IoT; and 3) studies on EC for IoT. The review of these studies provided a useful reference to us which helped us to develop our strategy.

A. *Data Transmission Path in IoT*

DTP optimization attract large attention for IoT because the DTP play a critical role in communication system and realizes the effective link and communication among different devices. Kim *et al.* [27] proposed a congestion classifier based on logistic regression and modified adaptive data rate control according to the congestion estimation in order to get an efficient data transmission in the long range wide area network. In [28], an improved ant colony optimization was adopted in clustered wireless network for multipath route discovery with multiple objectives including energy and distance. In [29], for maximization of IoT networks throughput, an adaptive load-balanced routing was presented. Moreover, some studies on data transmission for high reliability real-time industrial environments were also conducted [30], [31]. A tremendous work was done in previous studies on DTP. The results of the above studies provide good references for our research, but they did not consider the global parameters and different requirement for different data flows in IIoT.

B. *SDN for IoT*

The SDN is regarded as a crucial technique for IoT, intended for centralized control and separation of control and data flows [32], [33]. In [34] and [35], new frameworks that incorporate different information technologies for wireless sensor network and IoT were proposed, and some applications were given, respectively. Lu *et al.* [36] proposed an SDN-based TCP congestion control mechanism for solving of TCP problem. In [37], based on the SDN, Pang *et al.* combined multipathing and segment routing for traffic management to limit the storage requirements of IoT. The numerous works demonstrated that SDN or software defined IoT is impactful approach for IoT. However, there are few works on EC for data transmission in industrial applications.

C. *Edge Computing for IoT*

It is obvious that the edge computing IoT (edgeIoT) brings the computing resources close to IoT devices. Namely, by adopting the EC, the traffic load in core network can be clearly alleviated, thus, the network can achieve a new balance level, and the device-to-device communication delay strongly decreases [38], [39]. Due to the significant advantages of edgeIoT, more and more research attention is paid on edgeIoT. Wen *et al.* [35] proposed an EC architecture for mobile IoT, and in [40], a comprehensively survey on existing concepts integrating mobile EC (MEC) functionalities was presented and current advancement of the MEC was discussed. Particularly, Peralta *et al.* [41] presented a method to enhance energy efficiency of IoT node within Industry 4.0, through IoT and similar EC. A large number of studies show that EC provides a good selection in the fast-online computing. However, seldom studies focus on different data flows transmission for IIoT.

III. IIoT Framework With SDN and EC

A. Framework Review

In industrial applications, the communication networks have been progressed greatly. Both clustered and grouped network topologies have been developed and proven as manageable structures for IIoT. Since the current frameworks are limited by the constraints of communication latencies, fixed bandwidth, coverage, and unbalanced deployment of computing resources, therefore, it is poorly adaptable to emerging IIoT demands. In order to increase the flexibility, scalability, centralization IIoT, and balance the deployment of computational resources reasonable, SDN and EC are integrated into IIoT. Therefore, in the proposed solution, the cloud, SDN, EC, and the other subsystems constitute a novel framework, as shown in Fig. 2, wherein all components are connected by communication infrastructures. To better understand the system, we simplify the framework into East–West flow (IIoT), North–South flow (SDN) and Computing plane (EC).

All objectives, workmen, users, and smart terminals are abstracted into different kinds of network nodes as follows: ordinary nodes, cluster heads (CHs), and sink nodes. In the clustered IIoT, different function nodes and data centers jointly construct the data exchange subsystem. Evidently, CHs and ordinary nodes establish a small subsystem for data gathering and delivering, while this system has basic functions in M2M communication. In industrial application, due to the different services of the system, the data upload and offload need different time limit for different data flows. The solving of data transmission problem in this paper is focused on data transmission at data exchange subsystem.

In SDN subsystem, all communication flows are divided into control flow and data flow. In the system, an open source SDN controller Open Mul is adopted in the framework. Open Mul is an Openflow/SDN controller platform. The SDN controller is connected with key network devices, such as CHs. It is clear that these key nodes are amounted with controller interface, so they establish a link with SDN controller using OpenFlow protocol. IIoT nodes deliver the status parameter to SDN controller. Then, in the control layer, the controller makes decisions on data transmission control. In this paper, SDN is adopted to control the transmission path and transmitted power of M2M.

To get a reasonable assignment of computing resources, the EC severs (ECSs) are deployed in IIoT. Downward, these ECSs establish the link between nodes and SDN controller; upward, ECSs are connected to the cloud. Every ECS is typically miniature data and computing center, and is in the vicinity of nodes and SDN devices. In our scheme, EC is employed to derive the results in real time. The EC strategy reduces the time consumption and traffic load, comparing to the traditional computing models.

B. Working Process

The main working process of this framework is as follows. First, every ordinary node forwards the data to the CHs or some other ordinary nodes, according to the real applications. After the completion of data gathering in the whole cluster, CHs transmit the corresponding information to sink node or base station. Then, sink node sends this information to the cloud. Second, to realize a flexible control of the entire network, the statuses of all devices are uploaded to SDN controller and mapping databases. Once the SDN application layer is modified and certain application function is adjusted, the SDN controller gathers the parameters and uploads the tasks to ECS. Third, when a computing task, such as changing of transmission path, is given, the ECS optimizes the network parameters, such as power and hop path, and the optimization results are sent to SDN controller and IIoT devices. Lastly, after abortion of the control data, IIoT devices adjust their network conditions. Here, an adaptive DTP employs the same working process.

IV. Adaptive Data Transmission Algorithm

In this section, we describe how to solve DTP for different deadline constraints in the clustered-IIoT. As in Fig. 2, the proposed scheme can be divided into two steps: 1) optimal path coarse grain algorithm for low deadline situation and 2) adaptive transmission power algorithm for urgent situation. The main notations of this section are given in Table I.

A. System Model

1) Network Model: The IIoT network with V vertices and E edges is denoted as $G = \{V, E\}$ representing the set of nodes and links, where V represents the IIoT nodes (ND) and E represents the links. The communication range of nodes in the case of low real-time performance is R. Furthermore, if e_{ij} exists in set E, then nodes v_i and v_j can directly communicate with each other. Every node has its energy and network resources. The IIoT cluster can be denoted by $C_i = \{c_i, m_i\}$, where c_i and m_i represent the CH and its members, respectively. Therefore, we can use set $\Omega = \{C, L\}$ to simplify set G, with C vertices and L edges representing the set of CHs and links. The link value l_{ij} between c_i and $c_j, c_i, c_j \in C$, isgiven as follows:

$$l_{ij} = \begin{cases} 1, & c_i \bigcap c_j \neq \emptyset \text{ or } d_{CiCj} \leq R \\ 0, & \text{other} \end{cases} \tag{1}$$

where, d_{CiCj} is the Euclidean distance between c_i and c_j.

According to (1), we get the adjacency matrix A. Let us assume that in a cluster, every ND can directly communicate with CH; in other words, there is one hop between CH and ND. We denote the data transmission rate between CH and

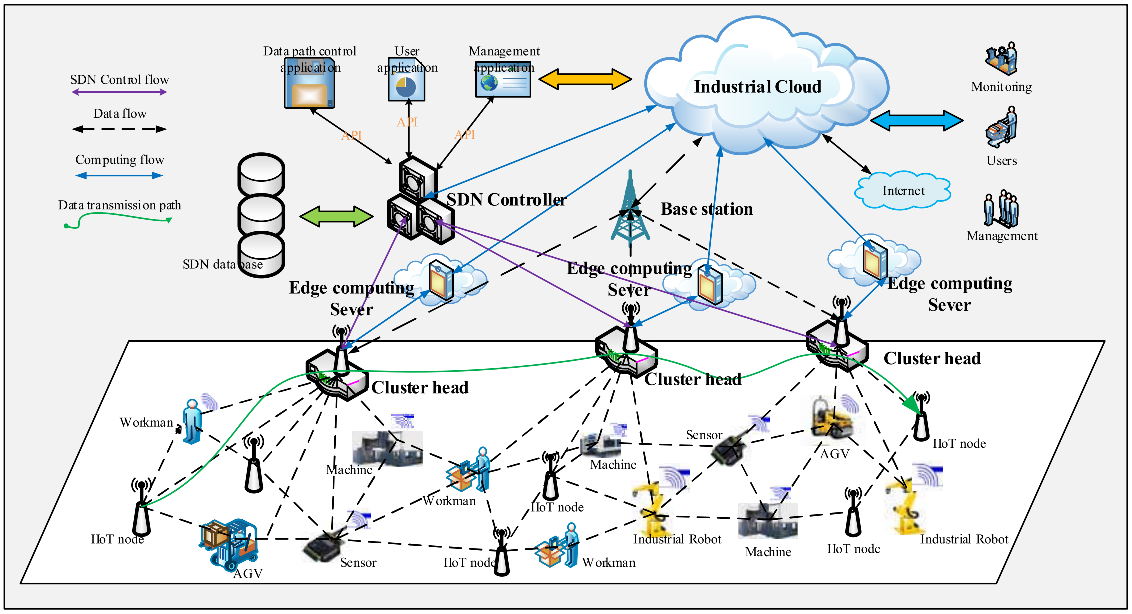

Fig. 2. Data transmission framework based on SDN and EC in IIoT.

TABLE I
NOTATION

Notation	Definition
c_i	The i-th cluster head
v_i	The i-th iot node
d_{CiCj}	Euclidean distance between c_i and c_j.
TR_{CN}	Data transmission rate between CH and ND
TP_{CC}	Data transmission rate of CH and CH
ξ_{ij}	The weight of transmission between cluster heads c_i and c_j
P_{ij}	The numbers of paths between v_i and v_j
H_{ij}	The numbers of hops between v_i and v_j
W	The transmission weight matrix of cluster heads
θ	The transmission data volume
PDD	Path difference degree
$PrePath$	Previous communication paths between v_i and v_j
$CurPath$	Current communication paths between v_i and v_j
φ	Path adopted frequency for communication between v_i and v_j
ϕ	Path adopted frequency set
Tc	Delay time constraint
$T_{\min}$	The minimal transmission time
P_t	Transmit power
P_r	Received power
$\alpha(d_0)$	The attenuation at reference distance d_0
β	The path loss exponent
R_{max}	The maximal transmission radius
P_{max}	The maximal transmission power
τ	Increasing power
λ	The increasing power coefficient
ε	The cost constant

ND as $\mathrm{TR_{CN}}$, and data transmission rate of CH and CH as $\mathrm{TP_{CC}}$ (in bps). To simply the problem, we assume that ND has the same communicate rate. In addition, CHs have high capacities of data rate and energy. Then, we formulate the data rate between the pair of nodes $\mathrm{PV} = \{v_i, v_j\}$ as

$$\mathrm{TR}_{ij} = \begin{cases} \mathrm{TR_{CN}}, & \exists\ \mathrm{PV} \in \mathrm{ND} \\ \mathrm{TR_{CC}}, & \forall\, \mathrm{PV} \in C. \end{cases} \tag{2}$$

We define ξ_{ij} as the weight of transmission between CHs c_i and c_j; if $i = j$, $\xi_{ij} = 0$, otherwise we formulate the weight value by

$$\xi_{ij} = l_{ij} \cdot \frac{P_{ij}}{H_{ij}} \cdot \frac{\mathrm{TR_{CC}}}{\mathrm{TR}_{ij}} \tag{3}$$

where P_{ij} and H_{ij} are the numbers of paths and hops between v_i and v_j, respectively. Apparently, the greater the value of ξ_{ij} is, the better the communication between v_i and v_j will be. The value of P_{ij} is formulated as

$$P = \begin{cases} 0, & \text{if } l_{ij} = 0 \\ 1, & l_{ij} = 1,\ d_{C_iC_j} < R \\ \left\| C_i \bigcap C_j \right\|, & \text{other} \end{cases} \tag{4}$$

where, d_{CiCj} is the distance between c_i and c_j. If $P_{ij} = 1$, then $H_{ij} = 1$, and if $P_{ij} = 0$, then $H_{ij} = \infty$, otherwise $H =_{ij}= 2$.

According to (3), it is easy to get the transmission weight matrix W of CHs, which is expressed as

$$W = \begin{bmatrix} \xi_{11} & \cdots & \xi_{1n} \\ \vdots & \ddots & \vdots \\ \xi_{n1} & \cdots & \xi_{nn} \end{bmatrix}. \tag{5}$$

Hence, according to (1) and (2), the transmission time $f\,(t_{ij})$ between c_i and c_j is defined by

$$f(t_{ij}) = \begin{cases} \frac{\theta}{\mathrm{TR_{CC}}}, & j \in C \bigcap i \in C \\ \sum_{p_{ij}} \frac{\theta}{\mathrm{TR_{CN}} \cdot H_{ij}}, & \text{other} \end{cases} \tag{6}$$

where θ is the transmission data volume, and p is the number of all paths with two hops between c_i and c_j.

For the path $p = \{v_i \ldots, c_k, c_{k+1}, \ldots, v_j\}$, where v_i and v_j represent start and end nodes, respectively, the forwarding time is defined by

$$T_p = \sum_{k \in p} f(t_{kk+1}). \tag{7}$$

The problem that we address at coarse grain level is stated as follows: when a multiple cluster $C = \{c_1, c_2, c_3, \ldots\}$ with the transmission data volume θ is given our objective is to find a routing path between v_i and v_j which meets the deadline time constraints.

Definition 1 (PDD): Let *PrePath* and *CurPath* be the sequence of previous and current communication paths between v_i and v_j, respectively. Then, PDD is defined by

$$\mathrm{PDD}_{\mathrm{curpath,prepath}} = \frac{\mathrm{Setdif(CurPath, PrePath)}}{\varphi_{\mathrm{CurPath}} \cdot |\mathrm{CurPath}|} \tag{8}$$

where the function of setdif (A, B) returns the number of different members of set A from set B, and φ is path adopted frequency for communication between v_i and v_j. φ is member of path adopted frequency set ϕ. Actually, there may exits multiple paths between v_i and v_j. However, if one path is too frequency used, load and energy unbalance is caused. Given delay time constraint Tc, we further formulate the current problem as

$$\begin{aligned} &\text{Max} \;\; \mathrm{PDD} \\ &\text{s.t.} \;\; t_{ij}^{\mathrm{cur}} \le T_C. \end{aligned} \tag{9}$$

To understand the problem better, we give an example to illustrate the above model and networks structure. As shown in Fig. 3, there are three CHs and ten NDs. Since, the member set of C_1 is $M_1 = \{1, 2, 3, 4, 8, 7, 10\}$ and the member set of C_2 is $M_2 = \{5, 6, 7, 8, 10\}$, the intersection of M_1 and M_2 is $\{7, 8, 10\}$. Moreover, we get the value of P_{12} which is equal to 3, and the hop number H_{12} which is equal to 2. According to (3), $\mathrm{TR_{CC}}{=}100\mathrm{TR_{ND}}$, so it is easy to get the weight value, $\xi_{12} = 150$. Furthermore, the weight value is $\xi_{23} = 50$. As $\xi_{12} > 0$, for a given pair of NDs (v_2, v_6) the multiple *path*s exist between them (C_1, C_2). Consequently, there are three routing paths that meet deadline, $\mathrm{Path}_1 = \{2, C_1, 7, C_2, 6\}$, $\mathrm{Path}_2 = \{2, C_1, 8, C_2, 6\}$, $\mathrm{Path}_3 = \{2, C_1, 10, C_2, 6\}$ given $\varphi_1 = \varphi_2 = \varphi_3 = 1$, thus $\mathrm{PDD}_{12} = 0.2$.

For given IIoT nodes v_i, v_j, the minimum hop number is $H_{ij} \ge \lfloor D_{ij}/2R \rfloor$. For any vertices v_k, its one hop neighbor vertice is v_f, So, the distance of two vertices must meet the condition of$D_{kf} \le \min\{R_f, R_k\}$. We assume that the communication range has the same value R; so $D_{kf} \le R$. Hence, for the nodes with the same communication range, the maximizing one-hop distance is R. For given IIoT nodes v_i and v_j, the straight line between them is LS_{ij}, and LS_{ij} can be covered by $\lfloor D_{ij}/2R \rfloor$ circles with radius R, and the minimal hop number is $\lfloor D_{ij}/2R \rfloor$.

According to the above description, we can get the minimal transmission time $T_{\min}$ for current network structure and state. For any link between vi and vj, the $T_{\min}$ is formulated by

$$T_{\min}^{ij} = 2\frac{\theta}{\mathrm{TR_{ND}}} + \left\lfloor \frac{D_{ij}}{2R} \right\rfloor \frac{\theta}{\mathrm{TR_{CH}}}. \tag{10}$$

2) Communication Range System: Assuming that the ith node transmit power is P_t, the received power P_r at jth node is defined by

$$P_r = P_t - \alpha(d_0) - 10\beta \lg\big(d_{ij}/d_0\big) \tag{11}$$

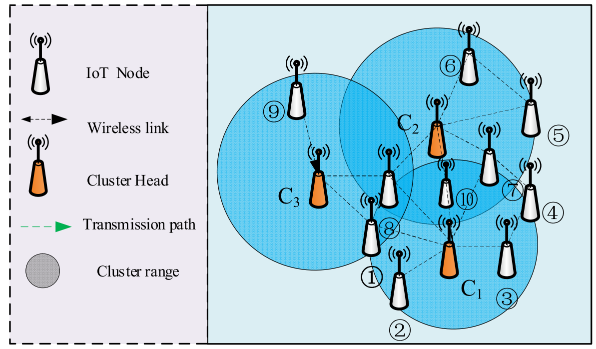

Fig. 3. Illustration of representative system model.

where $\alpha(d_0)$ is the attenuation at reference distance d_0, and the path loss exponent β varies depending on the network deployment scenario. For simplification, we assume d_0 is equal to one meter, thus, the formulation can be rewritten by

$$P_r = P_t - \alpha - 10\beta \lg(d_{ij}). \tag{12}$$

Definition 2: The maximal transmission radius $R_{\max}$ of node is the maximal transmission range obtained with the maximal transmission power $P_{\max}$.

Furthermore, only when P_r is greater than the definite power P_C, the communication link defined by (13) can be created

$$R_{\max} = 10^{\left(\frac{P_t - P_C - \alpha}{10\beta}\right)} = \gamma \cdot 10^{\frac{P_t}{10\beta}}. \tag{13}$$

The maximal communication range $R_{\max}$ is nondeceasing function. If the maximal communication range for a given function is *f,* then $f = R_{\max}$. We can derive f as follow: $(\partial f/\partial P_t) = (\gamma/10\beta) \cdot \ln 10 \cdot 10^{(P_t/10\beta)}$. Furthermore, $\beta > 0$, $\gamma > 0$, $P_t > 0$, so we can get that $(\partial f/\partial P_t) > 0$. In other words, f is an increasing function. Therefore, the maximal communication range $R_{\max}$ is a nondeceasing function. It is obvious that when P_t increases $R_{\max}$ also increases. Therefore, by increasing the transmission power, we can reduce the number of hops and transmission time.

It is well known that to provide a communication to the larger distance (i.e., to increase the communication radius) we have to increase the transmission power. On the other hand, to evaluate the cost of increasing transmission power, we define the cost function as follows:

$$Cp = \lambda e^{\tau} + \varepsilon \tag{14}$$

where τ is the increasing transmission power, λ is the increasing power coefficient, and ε is the cost constant.

The problem of adaptive power control is stated as follows: for a given delay time constraint T_c and set of all paths, our object is to find the minimal power control cost, which is defined as follows:

$$\begin{aligned} \text{Min} \;\; & Cp \\ \text{s.t.:} \;\; & t_{ij} \le T_c \\ & 0 < P_j \le P_{\max} \\ & T_c \le T_{\min}^{ij} \end{aligned} \tag{15}$$

Algorithm 1 Pseudocode of Coarse Grain Optimal Path Algorithm

Require: vi, vj, C, *Path_AllCH*, T_C, TR, W, ϕ
Ensure: *Path_selection*
1: $V \leftarrow < vi, vj >$, $Path_{ij} \leftarrow \varnothing$, $\varpi_0 \leftarrow 0$
2: From the set C, search the cluster head pair (c_i, c_j) of NDs v_i and v_j
3: Construct the communication cluster head pairs corresponding $CHPair{<}c_i,\ c_j{>}$ of v_i and v_j
4: Select all paths of $Path_{ij}$ between cluster head c_i and c_j, from *Path_AllCH*, according with W.
5: **for** $i = 0$ to $|Path_{ij}|$ do
6: $T_i = \sum t$ //calculating every path time by equation (6)
7: **if** $T_i < T_C$
8: *PathSS* $path_i$ //gathering the path
9: **end if**
10: **end for**
11: **for** $j = 0$ to $|PathSS|$
12: calculateϖ_j//calculating the path difference degree
13: **if** $\varpi_j > \varpi_0$ //determining whether ϖ_j is larger than the current maximum ϖ_0
14: $\varpi \leftarrow \varpi_j$;
// find the path with maximal path difference degree
15: *Path_selection* $PathSS_j$
16: **end if**
17: **end for**
18: $\varphi_{Path\_Selection}{=}\varphi_{Path\_Selection}{+}1$
19: Update ϕ
20: **return** *Path_selection*.

where t_j is the communication time after the transmission power changes, and P_j is the new transmitted power. According to (8), the problem actually finds the minimal power that meet the related constraints.

B. Coarse Grain Optimal Path Algorithm

In this section, we design an efficient method for the problem of a given structure of clustered-IIoT in low deadline situation. With regard to the industrial environment, an optimal path algorithm should be as simple as possible, and with a little processing time.

Based on the initial network, weight adjacency matrix A and weight matrix W, and by using the function of transmission time $f\ (t_{ij})$ between v_i and v_j, we calculate all paths between CHs c_i and c_j. Namely, this is a classical generation tree problem. Consequently, in our proposal, all paths of CH pair $(c_i,\ c_j)$ are found by some algorithms, such as depth first search (DFS), and stored into ECS or industrial cloud. The variable Path_{ij} represents all paths between c_i and c_j, and we represent all paths of every CH pair with the set *Path_AllCH*. Summing up all the aforementioned techniques, an online solution is designed. The proposed adaptive transmission optimization (ATO) based on the coarse grain optimal path algorithm is shown in Algorithm 1.

The key steps of the above algorithm are explained as follows. Line 1 represents the initialization of current network state, such as source and destination ND, CH node set, etc. As shown in lines 2 and 3, when SDN meets gets the transmission requirement of node v_i and v_j, according to the set C, algorithm finds the corresponding CHs and constructs communication CH pair $CHPair\ {<}c_i, c_j{>}$. Then, lines 4–10 derive all transmission paths between c_i and c_j from the set of *Path_AllCH*. Moreover, by calculating the transmission time, all path with threshold less than T_c are found and stored into set *pathSS*. Once a set of paths that meet time constraint is determined, the maximal PDD of these paths is found by lines 11–17. Lastly, algorithm returns the path with the maximal PDD. Time complexity of the main algorithm loop is $O(|\text{Path}_{ij}|)$, and the worst time complexity is $O(|\text{CH}|)$.

We use the example in situation Fig. 2 to explain the Algorithm 1. For finishing the communication between (v_2, v_6). According with the above analyses. If the forwarding times of paths are less than Tc, there are three paths. $\text{Path}_1 = \{2, C_1, 7, C_2, 6\}$, $\text{Path}_2 = \{2, C_1, 8, C_2, 6\}$, $\text{Path}_3 = \{2, C_1, 10, C_2, 6\}$. Assume the path1 is *PrePath*. So, given $\varphi_1 = 4, \varphi_2 = 2, \varphi_3 = 1$, PDD (1, *PrePath*)= 0.05, PDD (2, *PrePath*) = 0.1, *PDD* (3, *PrePath*) = 0.2. As PDD (3, *PrePath*) is the maximal value, $Path\_selection = Path_3$. In other words, path 3 finishes the communication between (v_2, v_6).

C. Adaptive Transmission Power for Fine Grain Algorithm

Algorithm 1 is designed for a common situation, in other words for a high transmission delay. However, the network usually faces with a low transmission delay. Therefore, in this part, the power was increased to create a strong link, so CHs can directly communicate with each other providing better performance, especially data rate. Therefore, we designed ATO for urgent situation, as shown in Algorithm 2.

The main steps are described as follows. First, SDN controller gains the constraint and related parameters of network, and then according to Algorithm 2, designs a new transmission path. The direct communication between CHs with increasing the transmission power $P(d(c_m, c_{m+1}))$ is found for all paths by lines 2–9, according with CHs distance $d(c_m, c_{m+1})$. Then, by recalculating the transmission time, the paths that meet the time constraints are found by lines 10–13. In lines 14–18, the minimal cost path is obtained. Lastly, algorithm returns a new path for the networks. Similar to Algorithm 1, the worst time complexity of main algorithm loop in is $O(|CH|^2))$.

Similarly, employing the example in situation Fig. 2 to show Algorithm 2. When the communication time between $(v_1,\ v_6)$ by adopting Algorithm 1 cannot meet the time deadline constraints Tc. For addressing the high-deadline situation, Algorithm 2 is used. First, calculate the corresponding CH pairs of $(v_1,\ v_6)$ with results $<c_1, c_2>$, $<c_3, c_2>$. Obviously, $R < d(c_1, c_2) < d(c_3, c_2) < R_{\max}$, and $T(c_1, c_2)$, $T(c_3, c_2) \leq T_c \leq T_{\min}$, so $CP(c_1, c_2) < CP(c_3, c_2)$. Then, select $\{v_1,\ c_1,\ c_{2,}\ v_6\}$ as the new transmission path with c_2 increasing the transmission power $P(d(c_m, c_{m+1}))$.

V. Evaluation Performances

In this section, the simulations are conducted to evaluate the performance of proposed method. First, we describe the simulation setup, performance metrics, reference schemes, and

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of cluster heads	10
Number of ordinary nodes	100, 200
Communication amount	100-900 Mb
Requirement for communication time	500-3000s
Maximal power communication range	50 m
Usual communication range	30 m
Custer head average channel rate	100 Mbps
Deadline Index I, II, III	1500, 2000, 3000 ms
Increasing power coefficient	1
Cost constant	0
Ordinary node average channel rate	1 Mbps

Algorithm 2 Pseudocode of Adaptive Transmission Power Optimization

Require: v_i, v_j, $Path_{ij}$, Tc, T_{min}
Ensure:, *Path_new*
for $i = 0$ to $|Path\_all|$
  Construct the communication all cluster head pairs corresponding of v_i and v_j, stored in $CP(v_i,v_j)$ from the $Path_{ij}$
  for $m = 0$ to $|CP|$
    Calculate distance pair of cluster head $d(c_m, c_{m+1}) = |c_m, c_{m+1}|$
    if $R < d(c_m, c_{m+1}) < R_{max}$
      $P_t(c_m)P(d(c_m, c_{m+1}))$ //increase the current transmission power
      $TR_{m,m+1} = TR_C$ // update the transmission rate
    end if
    Calculate the T_m by equation (6)
    if $T_i \leq T_C \leq T_{\min}$ // determining whether a new path meets the requirement
      NewPathSet Path_all[m]
    end if
  end for
end for
for $k = 0$ to | *NewPathSet*|
  Calculate Cp_k //calculating a new power changed cost
if $Cp_K < Cp_0$
  $Cp_0 \leftarrow Cp_k$; //find the path with the minimal cost
  Path_newNewpathSet[k]
end if
end for
return *Path_New*.

emulation scenarios. Then, the evaluation results are presented and discussed from various perspectives.

A. Simulation Setup

We developed the simulation framework and realized the proposed algorithm in MATLAB environment. We use multiple threads to simulate the related methods. One of threads is used to simulate the SDN controller, which collects network parameters regularly from network nodes. Then, state machine mechanism is adopted to emulate SDN controller actions by using the proposal, which involve in this paper such, routing path or increasing transmission power of CHs. The test cases were generated according to the IIoT node density and number of CHs. The framework for performance evaluation is presented in Fig. 5 and the main simulation settings are summarized in Table II.

B. Performance Metrics and Reference Schemes

To evaluate the performance of the proposed methods, we introduce the following performance metrics.

1) *Average Time Delay:* The average time delay represents the time needed for data transmission from the source node to the destination node.
2) *PDD:* As shown in Definition 1, this performance metric is used to measure the balance of transmission path. The energy consumption balance and load balance are closely related with this performance metric.
3) *Goodput:* The goodput is the QoS performance metric. The goodput is expressed as an amount of communication data successfully received at the destination within the required communication time.
4) *Throughput:* Throughput is the rate of successful message delivery over a communication wireless channel, in IIoT.
5) *Download Time From Server (DLTS):* DLTS is measured in the emulations to reflect the time delay performance from server of different computing frameworks in IIoT.

We compared the proposed method ATOP with the following methods.

1) *SPND*, wherein the source node and the destination node choose the shortest path using a method, such as Floyd or Dijkstra algorithm. The path is composed by IIoT NDs, and the node with maximal communication range is chosen.
2) *SPCN*, wherein as in SPND, the shortest path among NDs and CHs is chosen.
3) *CR*, wherein every node chooses its maximal rate node.

C. Evaluation Results

1) Average Time Delay: The average time delay of different methods for their best performance in terms of time delay and IIoT structure is presented in Fig. 4, which demonstrates the average time delay increases with the increase of data amount for all methods. The performances metric of average time delay for 100 and 200 NDs are presented in Fig. 4(a) and (b), respectively. The Fig. 4 shows that the average time delay increases with the raise of communication data amounts for the four methods. However, it is obvious that ATOP outperforms the others schemes in this metric with different data volumes. It dues to the optimization routing path of ATOP that selects the CHs as relay points with the higher communication rate and more communication resources. CR and SPCN achieve better performance than SPND, because CHs are in their communication path. The NDs has the higher delay time during the communication, so SPND method has the highest values for different data amounts as shown in Fig. 4. When the data amount is equal to 700 Mb, ATOP achieves the smallest average time delay, in other words our methods have reduced the time consumption. In the same way, ATOP shows better performance than other methods. Comparing to Fig. 4(a) for 100 NDs, ATOP has smaller value of average time delay than the others, and by increasing the number of nodes, more NDs could join in the communication among CHs.

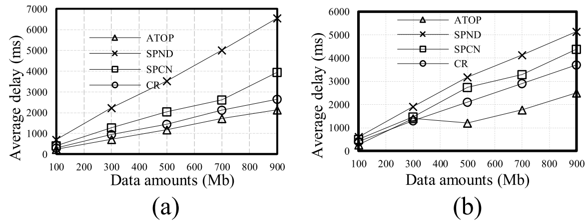

Fig. 4. Comparison of average time delay. (a) $n = 100$. (b) $n = 200$.

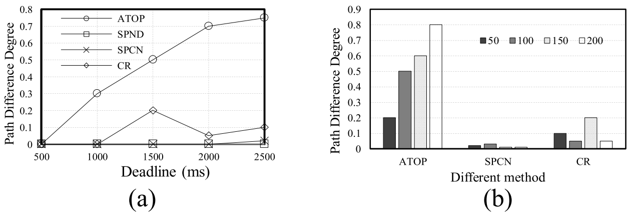

Fig. 5. Comparison of average PDD. (a) PDD in different data amount. (b) PDD in different ND number.

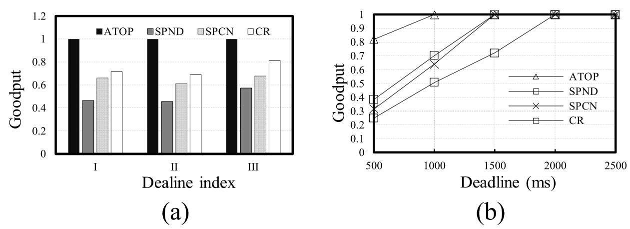

Fig. 6. Comparison of goodput performance. (a) Goodput for different deadlines. (b) Goodput for different methods.

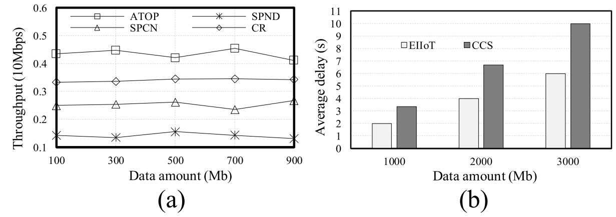

Fig. 7. Comparison of throughput and CODT in different levels. (a) Results of throughput. (b) DLTS in different method.

2) PDD: The PDD performance in different ways for the same number of NDs and CHs is presented in Fig. 5. In general, PDD of every strategy will increase with the increasing of deadline and ND number. In Fig. 5(a), with decreasing of deadline, PDD of ATOP also decreases, in other words, the smaller the value of deadline is, the more routing paths will be deleted from the candidate path set. When the deadline is larger than 1000 ms, the PDD is larger than 0.3. And if deadline is 1500 ms, the PDD of ATOP will reach 0.5. However, the other methods achieve the value near zero, especially for SPND and SPCN, because they usually select the same path without considering the path difference. Smaller PDD indicates more different paths are adopted to forward the information. Namely, ATOP provides more balanced load and energy consumption routing path, therefore, by employing the proposed method it can reduce energy unbalance and prolong network life. In addition, PDD results are obtained for different numbers of NDs in Fig. 5(b). Similarly, the other methods have the PDD value near zero. The PDD of ATOP increases with the increase of the number of NDs due to more selected paths.

Specifically, when ND number is 200, PDD of ATOP is 30, 15 times of SPCN and CR, respectively.

3) Goodput: This performance metric is a useful index for evaluation how successful is the data receiving from the source with the deadline constraint. The goodput for different deadline level and methods is presented in Fig. 6(a). In Fig. 6(a), it is obvious that when the deadline reaches different level, and goodput of the proposed method still has 100% successful receiving data rate, because the ATOP selects the most effective routing path and the method increases the transmitted power in order to get high communication rate. As presented in Fig. 6(a), CR and SPCN obtain good goodput because of CH takes part in data transmission. Moreover, it is clear that SPND obtains the smallest value because it adopts the NDs to construct the routing path. The curve of goodput and different deadline are presented in Fig. 6(b). With the increasing of deadline, the performance of goodput raises for all methods. Moreover, by using ATOP, the success receiving data rate is higher than 80%, when deadline is more than 500 ms. Hence, the ATOP can adapt to different deadline level. The other methods are questionable in urgent communication.

4) Throughput: The performance of throughput in different data amounts with different methods is presented in Fig. 7(a), it demonstrates that there are slight variations of throughput in different traffic load levels. In Fig. 7(a), we can observe that ATOP takes the highest throughput, as to choose the most effective path to forward the data. The average throughputs of ATOP,CR, SPCN and SPND are 0.43, 0.35, 0.25, 0.15 Mb/s, respectively. In other words, ATOP throughput get the max value in different data amounts. The proposed strategy provides the best performance of throughput, and then followed by CR and SPCN. Dues the data rate limitation of NDs, the SPND shows the worst performance in terms of throughput.

5) DTLS: We use DTLS to evaluate the delay performance from server in different computing frameworks. DTLS in our proposed edge IIoT (EIIoT) framework and cloud computing architecture is presented in Fig. 7(b) with different data amounts. We assume that the computational capacity of cloud computing server (CCS) is three times greater than EIIoT, and ND will spend three hops to download the data from cloud server. Further, CCS and our proposed framework have identical communication rate (1Mb/s). According to Fig. 7(b), with the increase of data amount, the average delays increase in both frameworks (CCS and EIIoT). From another perspective, the EIIoT demonstrates better performance than CCP. Namely, NDs consume less time for data transmission in EIIoT. Specially, when traffic amount reaches 3000 Mb, ED IIoT framework reduces more than 40% of downloading time from server comparing with CCS in light of direct connection between edge server and NDs. In additional, the

EIIoT framework represents better solution for industrial applications. Lastly, the proposed framework achieves the best performance in terms of DTLS.

VI. Conclusion

The IIoT represents the basis of smart factory and Industry 4.0. The IIoT effective transmission strategy for different delay level data flows directly determines the performance of the entire system. The traditional scheme faces some challenges. Due to the great progress of SDN, IWNs, and EC, IIoT has a new development opportunity. With the aim to improve the performance of data transmission, this paper conducts a study on IIoT and related domains. An adaptive transmission architecture with SDN and EC for IIoT is proposed. Meanwhile, a coarse-grained transmission path algorithm is provided for low deadline situation. By introducing the PDD, a balanced transmission path is obtained for all candidate paths, and fine-grained scheme including adaptive power method is adopted for urgent situations. The proposed method is validated by simulation. The results have demonstrated that proposed method represents a promising scheme for dealing with different data flows and can obviously reduce the pressure of the backbone IIoT.

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Xiaomin Li is currently pursuing the Ph.D. degree in mechanical and electrical engineering at the South China University of Technology, Guangzhou, China.

His current research interests include wireless sensor networks, IWN, and data mining.

Di Li was born in Anhui, China, in 1965. She received the B.S. and M.S. degrees in aerospace engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1988, and the Ph.D. degree in automation from the South China University of Technology, Guangzhou, China, in 1993.

From 1988 to 1990, she was an Assistant Engineer with the Qingdao Beihai Shipyard, China State Shipbuilding Corporation, Qingdao, China. From 1993 to 1998, she was an Associate Professor with the Guangdong University of Technology, Guangzhou, China. Since 1999, she has been a Professor with the Mechanical and Electrical Engineering Department, South China University of Technology. She has authored over 150 papers and holds eight patents. Her current research interests include high-performance embedded control systems, numerical control, and machine vision.

Dr. Li was a recipient of the First Prize for Science and Technology Development of Guangdong Province in 2009 and the Ding Ying Science and Technology Award in 2011.

Jiafu Wan (M'11) has been a Professor with the School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, China, since 2015. He has directed 16 research projects, including the National Key Research and Development Project, the National Natural Science Foundation of China, the High-Level Talent Project of Guangdong Province, and the Key Program of Natural Science Foundation of Guangdong Province. He has authored or co-authored over 140 scientific papers, including over 80 SCI-indexed papers, over 30 IEEE TRANSACTIONS/JOURNAL papers, 13 ESI Highly Cited Papers, and four ESI Hot Papers. He has over 4000 Google Scholar with an H-index of 32. His SCI other citations, sum of times cited without self-citations, reached 1204 times according to the Web of Science Core Collection with an H-index of 20. His current research interests include industry 4.0, IWNs, cyber-physical systems, IoT, cloud computing, embedded systems, and industrial robotics. His homepage can be visited at: http://www.cps-lab.cn/.

Mr. Wan is a Managing Editor for the *International Journal of Autonomous and Adaptive Communications Systems* and *International Journal of Arts and Technology*. He is a CCF and CMES Senior Member.

Chengliang Liu was born in Shandong, China, in 1964. He received the B.Eng. degree from the Shandong University of Technology, Shandong, and the M.Eng. and Ph.D. degrees from Southeast University, Nanjing, China, in 1991 and 1998, respectively.

He has been invited as a Senior Scholar with the University of Michigan, Ann Arbor, MI, USA, and the University of Wisconsin at Madison, Madison, WI, USA, since 2001. He is currently with the Institute of Mechatronics, Shanghai Jiao Tong University, Shanghai, China. His current research interests include mechatronic systems, MEMS/NEMS design, intelligent robot control, Web-based remote monitoring techniques, and 3S (GPS, GIS, RS) systems.

Muhammad Imran is currently with King Saud University Riyadh, Saudi Arabia, and is a Visiting Scientist with Iowa State University, Ames, IA, USA. He has authored or co-authored a number of research papers in refereed international conferences and journals. His current research interests include MANET, WSNs, WBANs, M2M/IoT, SDN, security and privacy.

Mr. Imran serves as a Co-Editor in Chief for the *EAI Transactions* and an Associate Guest Editor for IEEE ACCESS, *IEEE Communications Magazine*, *Computer Networks*, *Sensors*, the *International Journal of Distributed Sensor Networks*, the *Journal of Internet Technology*, *Wireless Communications and Mobile Computing*, *Ad Hoc and Sensor Wireless Networks*, *IET Wireless Sensor Systems*, the *International Journal of Autonomous and Adaptive Communications Systems*, and the *International Journal of Innovative Technology and Exploring Engineering*.