Low Latency Communication for Internet of Things

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***Abstract*—With the rise of IoT and social media, the major traffic flows in the future wireless network is not conventional phone traffic anymore. These rising traffic flows have stricter requirements on the latency performance and therefore need different resource utilization approaches. To resolve the resource utilization scheme of the upcoming new traffic flows, we envision the design of the open-loop communication for the devices. With the open-loop communication, all the data packets are directly transmitted without the need on neither feedback nor control signals and therefore increases the spectrum efficiency and reduce the latency. To be fully compatible with the current closed-loop cellular operations to maximize operating benefits, an autonomous communication scheme is further developed to adapt all communication scenarios in the heterogeneous wireless networks.**

I. INTRODUCTION

For current wireless communication system, the system first guarantees the existence of physical layer and then provide the corresponding service for the upper layer (down-top approach). Therefore, the resource of the wireless network, like frequency, time or the power, is consumed to provide precise control signals between receiver and transmitters. In the past, the conventional resource utilization scheme provides wonderful users experience because the most part of traffic flows in the network is phone traffic. For the phone traffic, it is required that all the datas should be arrived in sequences and stability is highly required. Therefore, establishing a stable physical layer link to service this traffic flow becomes the most important mission.

However, with the rise of IoT and social media traffics [1], the conventional phone traffic is not the most important mission anymore. These traffics have different requirements from the the phone traffic. For example, IoT traffic does not require all the data arriving in sequences. For social media like Live video, because humans only care about what is happening currently instead of the past , it may have stricter requirements on the low-latency performance instead of recovering the past datas. To build up the fifth generation (5G) system, we should rethink about how to utilize limited resources in the system to service different kinds of traffic flows under different surrounding environments. That is, all the resource should be utilized from top-down approach instead of the conventional down-top approach.

On the other hand, with the rise of the number of devices, it becomes harder to provide a stable physical layer link solely via large amounts of control signals [2]. The challenges of down-top approach includes:

1) The applications of IoT or social media care about the data transmission latency. However, the current 4G system spends lots of time on waiting for the next control signal. For example, in LTE system, HARQ scheme needs to spend additional 4 subframes time to wait for the acknowledge (ACK) or the negative acknowledge (NACK) for each 4 transmitted subframes, which harms the efficiency of spectrum and needs additional latency to wait for these information back. In addition, for the multi-hop environment like D2D in LTE for the range extension application [3], the latency at each hop is accumulated and the closed-loop is further infeasible.
2) The transmitters may be energy-harvest devices and the energy only can support for single-way transmission. After the energy-harvest device finishes its transmission, it may run out of all the energy and goes into the sleeping mode. In this case, the control signals cannot such channel state information or acknowledge (ACK) of transmission may bring additional energy burden for the energy-harvest devices.
3) It is general to assume that the control signal (the packets with a small size) can be transmitted without any cost and be successfully received. It is a reasonable assumption only while the number of devices is small. While the number of devices increases, these control signals compete with others for scarce radio resources, which results in the collapse of systems.

In this works, we focus on providing low-latency service in the uplink scenario, which may be the major traffic flows of the IoT application. To reduce the latency, one of the effective method is to alleviate the tremendous amount of control signals in the air interface. We propose the idea of open-loop communication concept. In the open-loop communication, the receiver does not provide any feedback information like channel state information, ACK/NACK information to the transmitter side. However, without the channel state information, the transmitter side cannot choose the best channel to transmit data. Without these information, an effect scheme to provide a reliable communication is utilizing repetition transmissions, which may further decrease the latency performance. Therefore, whether open-loop communication can simultaneously provide reliability and smaller latency may be a question.

The scenario that the devices are at the edge of service region and try to upload their data through mutli-hop approach

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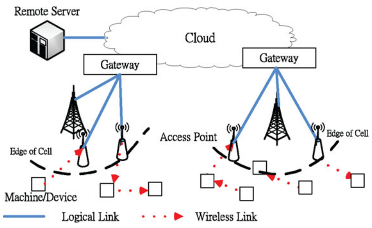

Fig. 1. We consider the scenario that the network consists of multiple transmission pairs and their spatial distribution follows PPP. Each transmitter has minimum distance R between its receiver. For each transmission pair, there are K orthogonal channels and devices operating in the closed-loop communication can choose the best one channel to transmit data.

to reach the nearby access point, like data aggregator (DA). However, many factors may affect the performance, which include density of the transmitters, battery capacity of the devices, and the distance to the receiver side, etc. To analyze the interference, a powerful mathematical tool, stochastic geometry, is adopted to evaluate the interference level for different spatial distribution in a wireless network [4]. The system performance like the outage probability can be analyzed and gives the insight about the communication system with different transmitter densities. We show the superior performance of open-loop communication over closed-loop communication in the high density environment. To facilitate devices determining a better operating mode between the closed-loop and the open-loop communication, we propose an autonomous adaptive scheme based on the sequential detection to minimize the learning time.

II. SYSTEM MODEL

A. Network and Channel Models

We consider a network which is composed of different IoT devices located nearby service region of the base station, as shown in Fig. 1. Because the IoT devices may be energy limited and does not have enough energy to access the base station directly all the devices need to access the base stations or DA via multi-hop approach. Therefore, there exists multiple transmission pairs simultaneously. For general system assumptions, all the transmitters are spatially distributed with locations specified by a homogeneous Poisson point process (PPP) Φ_0 with density λ_0. There are K different orthogonal frequency bands denoted as the set $\mathcal{K} \triangleq \{1, \ldots, K\}$. Because of the homogeneous property, we consider a typical receiver located at the origin, which can represent the general cases. We denote $H_k, k \in \{1, \ldots, K\}$ as channel power gain from a transmitter to its desired receiver in channel k. For Rayleigh fading channel, H_k is a random variable of exponential distribution with mean u_0^{-1} [4]. We denote the set of transmitters choosing the kth channel to transmit data as Φ_k and denote λ_k as the density of Φ_k. Therefore, the relation between Φ_0 and Φ_k can be expressed as $\Phi_0 = \sum_{k=1}^{K} \Phi_k$ and $\lambda_0 = \sum_{k=1}^{K} \lambda_k$.

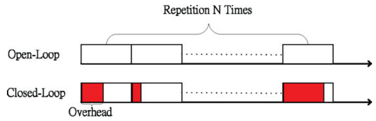

Fig. 2. Transmission schedule in the time domain for the open-loop and the closed-loop. The white part is the transmission for the data and the red part is the control signals like feedback channel state information.

B. Interference and Successful Probability

The aggrregated interference from Φ_k to this typical receiver at the channel k is denoted as $I_k = \sum_{x \in \Phi_k} H_{x,k} P_0 ||x||^{-\alpha}$, where P_0 is the transmission power and $H_{x,k}$ is the channel fading gain from other transmitter x to the typical receiver. $||x||$ is the distance between transmitter x and the typical receiver, α is the path loss effect coefficient. Through proper power control, the maximum transmission radius is the same for each transmitter. We assume that all transmission pairs have distance R. Then the received signal is $H_k P_0 R^{-\alpha}$ and the successful transmission can be defined as via signal-to-interference ratio (SIR) satisfying

$$SIR = \frac{H_k P_0 R^{-\alpha}}{I_k} \geq \theta, \tag{1}$$

where θ is the threshold of SIR. We ignore the noise here because the performance of the successful transmission is dominated by interference in the high density environment. To describe the property of the probability distribution of I_k, the moment generating function (MGF) is a suitable tool. In [4], it is shown that the MGF of the random variable I_k is

$$\mathbb{E}\left(e^{-sI_k}\right) = exp\left(-\lambda_k P_0^{\frac{2}{\alpha}} s^{\frac{2}{\alpha}} K_\alpha\right), \tag{2}$$

where $K_\alpha = 2\pi^2 / \left(\alpha \sin 2\pi\alpha\right)$.

III. OPEN-LOOP AND CLOSED-LOOP MODELS

We illustrate the transmission schedule in the time domain for the open-loop and the closed-loop in Fig. 2. To discuss about the most fundamental performance of the open-loop, we assume that open-loop only takes repetition code to improve the reliability of the transmissions. Of course, such repeating times can be reduced by further powerful network coding as shown in [5] or other coding schemes. For the closed-loop, it needs to transmit the same data only if the receiver side cannot receive the data successfully. However, we do not assume that the control signals can always be received successfully. If the transmitter side cannot decode these control signals successfully, the transmitter also needs to wait for additional times (detail descriptions are in Section III-B1) before transmitting the next data.

A. Open-Loop Communication

For the open-loop communication, each transmitter and receiver does not exchange any control signal like channel estimation data or ACK/NACK. To combat fading channels, the repetition scheme is adopted. The repetition scheme can be applied in frequency, time and spatial domain and provide the lower-bound performance for the open-loop communication. Here, we consider the scenario that transmissions repeat in the time domain, as shown in Fig. 2. The number of repetitions N depends on requirement of the system like the guaranteed delay or the required outage probability.

1) Successful Transmission Probability Analysis: Because all the transmitters choose a channel randomly, the set of transmitters choosing the kth channel Φ_k also follows PPP property. Due to without any information, what transmitters can do is to choose one of the channels from $\mathcal{K}$ and transmit data directly. Then the density λ_k of the process Φ_k is $\frac{\lambda_0}{K}$. The probability of a successful transmission for a transmitter choosing kth channel is the probability of satisfying eq. (1)

$$\begin{aligned} P^o_{success|k} &\triangleq \mathbb{P}\left(\frac{H_k P_0 R^{-\alpha}}{I_k} \geq \theta\right) \\ &= \mathbb{E}\left(exp\left(-u_0\frac{I_k\theta}{P_0 R^{-\alpha}}\right)\right) \\ &= \exp(-\lambda_0\frac{1}{K}u_0^{2/\alpha}\theta^{2/\alpha}R^2K_\alpha), \end{aligned} \tag{3}$$

where the last equation follows from the fact of eq. (2). Then the overall expected successful transmission probability p_s is

$$\begin{aligned} p^o_s &\triangleq \sum_{k=1}^{K} P^o_{success|k}\mathbb{P}(\text{choosing } k\text{th channel}) \\ &= \frac{1}{K}\sum_{k=1}^{K}\exp\left(-\lambda_0\frac{1}{K}u_0^{2/\alpha}\theta^{2/\alpha}R^2K_\alpha\right). \end{aligned} \tag{4}$$

2) Spectrum Efficiency Analysis: For the open-loop communication, each data is transmitted N times repetitively. The transmission repetitions introduce additional redundancy into the communication and mitigates the spectrum efficiency. For a transmission pair, what it mostly cares about is how much data they can transmit in each time slot in average. With transmission repetitions, a failed transmission happens only if all the transmission repetitions fail but only one data frame can be received no matter how many other repetitions are received successfully. Therefore, we can define the spectrum efficiency for the open-loop communication performance lower bound without network coding or other powerful coding as

$$T^o \triangleq \frac{1-(1-p^o_s)^N}{N}. \tag{5}$$

That is, we care about how much the expected data the transmission pair can support in each time slot in a long run.

B. Closed-Loop Communication

In the closed-loop communication, each transmitter needs to get the information from the receiver side to optimize the physical link. After transmitting the channel training signals, the receiver transmits the necessary information like the channel estimation result back to the receiver. In generally, we always assume that this information can be successfully received by the transmitters. However, it is not the case in the high density environment due to the scarce spectrum resource. These feedback information should act like general information datas and may need retransmissions if failure occurs. Therefore, the total amount of feedback information is random and may occupy all the transmission time as the red part shown in Fig. 2. In this section, we start with the successful transmission probability and analyze the additional control signals caused by the failed transmissions of the feedback information.

1) Successful Transmission Probability: In the closed-loop scenario, with the help of feedback information, all the transmitters do not choose the channel uniformly. Instead, they can choose the best channel based on the feedback information. Denote the best channel fading between typical transmitter and receiver as $H_{max} = max\{H_1, H_2, \ldots, H_K\}$ and the probability of accessing the channel k as p_k. Because all the transmitters have the same statistical channel property, the density of transmitters λ_k in the channel k can be expressed as

$$\lambda_k = \lambda_0 p_k, \tag{6}$$

where p_k can be expressed as

$$\begin{aligned} p_k &= \mathbb{P}(max\{H_1, H_2, \ldots, H_K\} = H_k) \\ &= \int_{H_k=0}^{\infty}(1-e^{-u_0 H_k})^{K-1}u_0 e^{-u_0 H_k}dH_k \\ &= \frac{1}{K}. \end{aligned} \tag{7}$$

Then the successful transmission probability $P^c_{success|k}$ is

$$\begin{aligned} &P^c_{success|k} \triangleq \mathbb{P}\left(\frac{H_{max}P_0R^{-\alpha}}{I_k} \geq \theta\right) \\ &= \mathbb{E}\left(1-\left(1-\exp(\frac{-I_k\theta}{P_0R^{-\alpha}}u_0)\right)^K\right) \\ &= 1-\sum_{k=1}^{K}\binom{K}{k}(-1)^k\exp\left(-\lambda_k\left(\frac{\theta u_0 k}{R^{-\alpha}}\right)^{2/\alpha}K_\alpha\right), \end{aligned} \tag{8}$$

the last equality follows from the fact of eq. (2). Then the successful transmission probability for the closed-loop communication p^c_s is

$$p^c_s = \sum_{k=1}^{K}p_k P^c_{success|k}. \tag{9}$$

2) Spectrum Efficiency Analysis: To analyze the spectrum efficiency in the closed-loop, we first need to identify the amount of control signals for each transmission pair. At the beginning of the transmission, the transmitter should transmit the channel training signal instead of channel state information. At the end of time slot, the receiver feedbacks ACK/NACK to the transmitter side. Here, we aggregate these control signals to be one and assume that, for each transmission, they occupied $s, 0 \leq s \leq 1$ ratio of a time slot. Because the feedback information is also another type of packet, we cannot ignore the failure transmissions of these control signals, especially while the radio resource is scarce.

Because each receiver has its own transmitter, we can assume that the density of receivers which will feedback information has the identical density λ_k in the channel k. Successful transmission criteria is the same with that of transmitters, that is eq. (1). If the feedback information is not received successfully by the transmitter or time-out, all the feedback procedures repeat and pay additional s ratio of the time slot. Therefore, the total amount of control signals is not a constant but a random vairalbe, as the red part illustrated in Fig. 2. Once the transmitter successful receives the feedback information, this transmission pair just starts to transmit data and access the best channel according to the received information. The retransmission time n of feedback information is no more than $\lfloor \frac{1}{s} \rfloor$ or the control signals will occupied all the time slot. Then f_n is the probability of successful transmission of feedback information at nth times is

$$f_n = \begin{cases} p_s^c(1-p_s^c)^{n-1}, n = \{1, \dots, \lfloor \frac{1}{s} \rfloor\} \\ 1 - \sum_{n=1}^{\lfloor \frac{1}{s} \rfloor} f_n, \text{failure} \end{cases} \tag{10}$$

The expected occupied ratio $\rho \triangleq \mathbb{E}(s)$ in a time slot is $\rho = s\sum_{n=1}^{\lfloor \frac{1}{s} \rfloor} n f_n + (1 - \sum_{n=1}^{\lfloor \frac{1}{s} \rfloor}) \times 1$. The second term is due to the fact the remaining time of a time slot is not long enought to transmit a control signal. Then the spectrum efficiency of the closed-loop communication T^c is

$$T^c = p_s^c(1-\rho). \tag{11}$$

C. Performance Analysis Result

We show the comparison between the open-loop and the closed-loop in this section. For the closed-loop, $s = 10\%$, 20%, 30% of the control signals are considered. To combat the interference in the open-loop communication, the data repetition time N with $2, 4, 6$ are applied in one-shot. The other parameters are set as: SIR threshold $\theta = 4$, transmission distance $R = 10$, mean of channel fading $u_0 = 1$, path loss $\alpha = 4$.

The data arrival rate is assumed to follow Markovian arrival processes. We also assume that all the datas follow first come first service (FCFS) policy. The service time of the open-loop is a constant N, but it is hard to specify the exact distribution for service time of the closed-loop. Therefore, we can model each wireless link as a M/G/1 queueing model in the closed-loop and the open-loop. The mean data arrival rate is set as $1/30$ per time slot.

Fig. 3 illustrates the mean required time slot for each successful transmission data after data enter into the devices. We can find that, to finish a complete data subframe transmission, the latency performance of the open-loop is better than that of the closed-loop especially while the density of the devices is large. It is the reason that the control signals occupies the limited radio resource and the most of data still are queued in the devices.

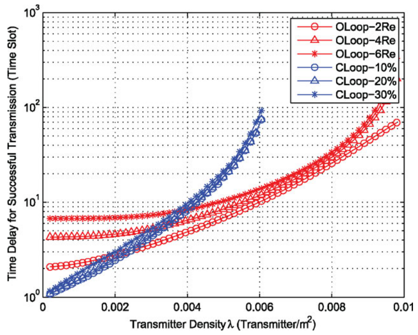

Fig. 3. Latency analysis for a successful transmission of open-loop and closed-loop under different densities of devices. We can find that the closed-loop communication has worse latency performance while the density increases.

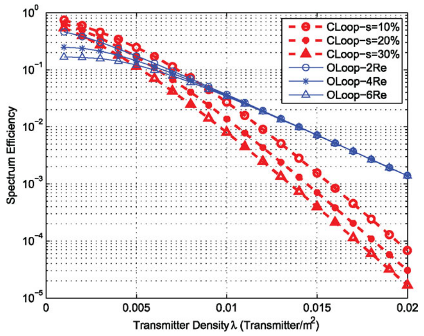

Fig. 4. Spectrum efficiency for the open-loop communication and the closed-loop communication under different densities of devices. The closed-loop and the open-loop is suitable for the low and high density environment respectively.

The similar phenomenon can also be observed in the spectrum efficiency analysis. From Fig. 4, we can find that the open-loop communication can help to improve the spectrum efficiency up to $10dB$ while the density λ_0 is about 2×10^{-2}. Such potential gain comes from the saving cost of transmitting control signal. It implies that the open-loop communication is more suitable for the future network where the density of transmitters is larger no matter in the viewpoint of latency or spectrum efficiency. The reason of the result is that the closed-loop spends most of radio resource to transmit the control signals but it cannot get enough benefits to increase the transmission rate of the data.

IV. AUTONOMOUS COMMUNICATION MECHANISM

The analyses above show that the closed-loop and the open-loop communication are suitable for different operating environments. In the high-density environment, the spectrum resource is so limited that most of the transmissions may fail due to interference and multiple access. Therefore, any transmission pair should not waste any resource to feedback information and therefore, the open-loop communication obtains more advantage here.

To enable autonomous communication based on the analyses above, each transmission pair should determine its transmission mode according to the environment. A possible solution is that the transmitter operates in the closed-loop for a period of time and learn which communication mode is suitable via feedback information. To minimize this learning period, we proposed the sequential detection to help transmitters to adopt their own operation mode. We divide the transmission times into two parts: N_L time slots of the learning period and N_T time slots of the transmission period. In N_L time slots of the learning period, the transmission pairs operate in closed-loop mode. In N_T transmission periods, the transmitters transmits data according to its own decision from the learning period respectively.

A. Problem Formulation by Hypothesis Test

From the analyses above, we know that the critical key point to determine whether utilizing the open-loop depends on the density of the operating environment. In Fig. 4, we can find that once the occupied ratio s is determined, there exists a threshold density λ_γ between the closed-loop and the open-loop. This threshold can be applied to determine which communication mode should be taken by the transmitter. That is, each transmitter actually makes a decision between two hypotheses:

$$\begin{aligned} H_1 &: \lambda_0 > \lambda_\gamma \\ H_0 &: \lambda_0 < \lambda_\gamma, \end{aligned} \tag{12}$$

where λ_γ denotes as the transition density between the closed-loop and the open-loop mode. H_1 and H_0 denote the hypotheses corresponding to the open-loop is better than the closed-loop or not respectively. Because λ_0 is uncertain to the transmitters, we assume that the distribution probability p_λ of the density is random variable with uniform distribution and $\lambda_0 \in [\lambda_\gamma - \lambda_d, \lambda_\gamma + \lambda_d]$. Therefore, the *priori* probability is $P(H_0) = P(H_1) = \frac{1}{2}$. Then the conditional probability of the density $p_{\lambda|H_j}$ on H_j is

$$p_{\lambda|H_j} = \frac{1}{\lambda_d}, j = \{0, 1\}. \tag{13}$$

During the learning period, the transmitters receive feedback information $\{y_n | n = 1, \ldots, N_L\}$ indicating the successful transmission or not. We denote $y_n = 1$ as successful transmission and $y_n = 0$ as failed one. Because the channel fading gains are independent for each transmission, it is reasonable to assume that y_ns are identically independent distributed random variables. Here, we use the notation $p^c_{s|\lambda}$ to represent p^c_s in eq.(9) conditioned on $\lambda_0 = \lambda$. Then we can express *posteri* probability $p_{y_n|H_j}$ conditioned on H_1 and H_0 is

$$\begin{aligned} p_{y_n=1|H_1} &= \int_{\lambda_\gamma}^{\lambda_\gamma+\lambda_d} p^c_{s|\lambda} p_{\lambda|H_1} d\lambda \\ p_{y_n=1|H_0} &= \int_{\lambda_\gamma-\lambda_d}^{\lambda_\gamma} p^c_{s|\lambda} p_{\lambda|H_0} d\lambda, \end{aligned} \tag{14}$$

and $p_{y_n=0|H_1} = 1 - p_{y_n=1|H_1}$, $p_{y_n=0|H_0} = 1 - p_{y_n=1|H_0}$.

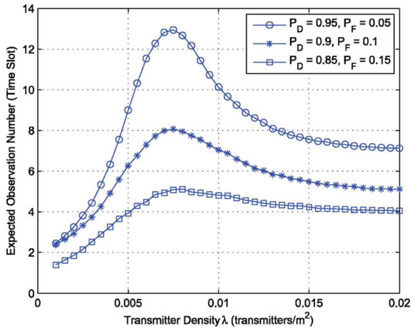

Fig. 5. Expected observation time slots for different requirements of P_D and P_F.

B. Decision Rule

The sequential detection needs to calculate the *log-likelihood ratios* of the received observation. The *log-likelihood ratios* after n observations $\Lambda(y_1, y_2, \ldots, y_n)$ is

$$\Lambda(y_1, y_2, \ldots, y_n) = \log \frac{p(y_1, y_2, \ldots, y_n | H_1)}{p(y_1, y_2, \ldots, y_n | H_0)}. \tag{15}$$

In the following, we express $\Lambda(y_1, y_2, \ldots, y_n)$ as Λ_n to simplify notification. The decision at time n denoted as D_n can be described as

$$D_n = \begin{cases} H_1, & \text{if } \Lambda_n > \log B \\ H_0, & \text{if } \Lambda_n < \log A \\ \mathit{continue}, & \text{if } \log A \le \Lambda_n \le B. \end{cases} \tag{16}$$

To guarantee the detection probability larger than P_D and the failed detection probability smaller P_F, the decision threshold A and B can be set as

$$A = \frac{1 - P_D}{1 - P_F}, B = \frac{P_D}{P_F}. \tag{17}$$

If D_n is H_1 or H_0, the sequential detection is completed. If D_n is *continue*, the detector continuously operates in the closed-loop to take observation until decision H_1 or H_0 is made.

V. SIMULATION AND IMPLEMENTATION ISSUES

A. Simulation

In the following simulation, the parameters setting are $\theta = 4$, $R = 10, u_0 = 1, N_T = 5$ and the results are averaged over 5000 times. The control signal ratio in the closed-loop are $s = 10\%$ and the open-loop with repetition times $N = 2$.

In Fig. 5, we simulate the expected observation times of our proposed scheme conditioned on different value of λ_0. We can find that as the required P_D and P_F are stricter, the more observation times are required. Because the transmitters are operating in the closed-loop during the learning period, the longer learning time may further mitigate the transmission performance if the closed-loop is not the best transmission mode. Therefore, the better requirement of P_D and P_F pair do not guarantee better transmission throughput.

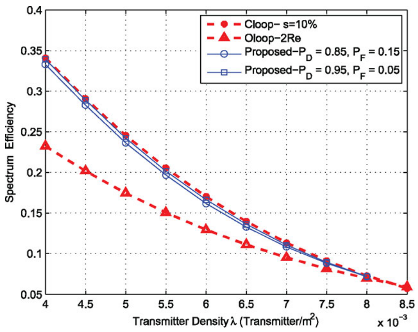

Fig. 6. Sequential detection in the low density environment. Cloop refers to always-closed-loop scheme with $s = 10\%$ and Oloop refers to always-open-loop scheme with $N = 2$. With better requirement of P_D and P_F, transmitters can approach the best operation mode if the environment is in low density environment.

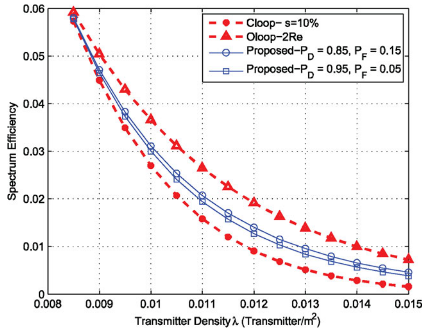

Fig. 7. Sequential detection in the high density environment. The proposed scheme can perform better than always-closed-loop scheme and approach to always-open-loop scheme in the high density environment.

We compare the performance of the proposed scheme with that of always-closed-loop and always-open-loop scheme under different densities environment in Fig. 6 and Fig. 7. Fig. 6 and 7 refers to the environment with low and large density environment respectively. For a device, without the information about the environment, the device cannot always choose the best communication mode. Therefore, the always-closed-loop and always-open-loop scheme refers to the optimal or worst performance depending on operating environment. The results show that our proposed scheme can successfully help transmitters to operate in a suitable mode to get further better performance no matter in the high or low density environment. Here, we need to note that the loss of performance in the high density environment comes from the repetitions of learning period N_L. For a more stable environment, like in-door environment, machines or devices just need to learn a period of time and operate in a correct mode forever.

B. Implementation

In this section, we discuss about the possible issues while implementing open-loop communication into the wireless communication system. One of the challenges in the downlink scenario is device discovery problem [6]. For example, the energy-harvest devices may go into the sleeping mode immediately after transmitting the collected data. In such case, the DA with closed-loop communication can broadcast the data and heard whether the objective device feedback ACK or not. However, there is no ACK design in the open-loop communication and how DA transmits the downlink data to the device when it wakes up immediately may be an important issue in IoT application. Other possible issue are interference alignment and cancellation. Information theory shows that an optimized handling may lead to significant capacity increases in the precise channel-state information (CSI) at the transmitter. However, with the open-loop communication, the instantaneous CSI may not be available. Therefore, the interference cancellation and alignment may rely on the information with longer time scale such as location information [7].

VI. CONCLUSION

In this paper, the performance of open-loop and closed-loop communication under the different environments are analyzed. Based on the analyses, the open-loop communication is suitable to be the first step toward utilizing the resources directly without the control signals. With the reduction of these control signals, the open-loop communication can improve the latency performance and the spectrum efficiency simultaneously, especially in the environment with large density of devices utilizing non-orthogonal multiple access (NOMA) simultaneously [8]. Therefore, the benefit of the open-loop communication is not only restricted in the view point of the physical layer but also the network layers.

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