Available Range of Different Transmission Modes for Ultra-reliable and Low-latency Communications

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***Abstract*—Ultra-reliable and low-latency communications (URLLC) are considered as one of the typical scenarios in the fifth generation of wireless communications, which not only have stringent quality-of-service (QoS) requirement on packet loss and end-to-end delay but also have high network availability requirement. In this work, we study *available range* for URLLC with different transmission modes, including cellular mode, device-to-device (D2D) mode, and a hybrid mode that consists of cellular links and D2D links. The available range of a certain link is defined as the maximal communication distance of the link, within which the QoS and availability can be satisfied. The available ranges of cellular and D2D links are maximized with different transmission modes. The analysis shows that there is a tradeoff between the available range of cellular links and that of D2D links. Numerical results show that compared with D2D mode and cellular mode, the hybrid mode can double the available ranges of cellular and D2D links. By increasing antennas at the base station, available range of D2D links can be extended.**

***Index Terms*—Available range, cellular mode, D2D mode, hybrid mode, ultra-reliable and low-latency communications.**

I. Introduction

Supporting ultra-reliable and low-latency communications (URLLC) is one of the major tasks in the fifth generation of wireless communications [1]. Applications in URLLC include ultra-reliable machine-type communications and haptic human-to-machine communications, such as autonomous vehicles, factory automation, and remote control [2, 3]. These applications have strict requirement on end-to-end (E2E) delay (e.g., 1 ms) and reliability (e.g., 10^{-7} packet loss probability).

Ensuring the quality-of-service (QoS) of URLLC in cellular networks has been studied in existing literatures, where all the nodes (e.g., sensors and users) first upload packets to base stations (BS) and then the target nodes download packets from the BSs. By taking uplink and downlink transmission delay and queueing delay into consideration, the studies in [4] show how to jointly design resource allocation for uplink and downlink transmission, where Shannon capacity is used to characterize data rate. With low transmission delay, the blocklength of channel codes are performed in finite blocklength regime. As a result, Shannon capacity is not achievable [5]. With the achievable rate with finite blocklength, uplink and downlink resource allocation has been studied in [6] and [7], respectively. For autonomous vehicle and factory automation, short packets generated by each node are requested to multiple nearby nodes [2, 8]. Therefore, device-to-device (D2D) mode may offer a lower E2E delay compared with cellular mode and broadcast could be helpful for saving bandwidth and reducing control overhead.

Network availability is another key performance metric of URLLC. It is defined as the probability that the QoS (i.e., reliability and latency) of users can be satisfied in a wireless network [2]. For applications in URLLC, the required network availability is close to 1, e.g., 99.999 % [9]. Due to shadowing, it is very challenging to guarantee availability with a single link [6], and hence we need to exploit macro-diversity [9]. To reduce handover failures, which deteriorate network availability, multiple BSs can transmit the same packet on the same time-frequency resource [10]. Studies in [8] show that direct transmission and retransmission via a BS can be used together to improve availability. Although some ideas for improving availability have been proposed in [8–10], the analyses are based on Shannon capacity, which is not suitable for URLLC.

In this work, we study how to guarantee the QoS and network availability for URLLC with different transmission modes. Different from existing studies that assume each pair of nodes are closely located and are able to communicate with each other [8], we study how to extend the *available ranges* of the cellular and D2D links, where the available range of a link is defined as the maximal communication distance of the link, within which both QoS and availability can be ensured. The achievable rate in finite blocklength regime is applied in our analysis, and the results show that there is a tradeoff between available range of cellular links and that of D2D links. Numerical results show that with lognormal distributed shadowing, network availability requirement can not be satisfied only with cellular mode or D2D mode. With hybrid mode, by increasing the number of antennas at the BS, we can either increase the available range of cellular links or that of D2D links under the QoS and availability constraints.

II. System Model

Consider a cell, where the BS is with $N_{\rm t}$ antennas and each of the single-antenna users either has a packet to transmit or stays dumb at a certain time. The active users that need to transmit packets are referred to as sensors for simplicity. As

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illustrated in Fig. 1, the users lie in the concerned area with respect to (w.r.t.) a certain sensor require the packet from the sensor, which are referred to as target receivers of the sensor. The range of concerned areas depends on the kind of applications, say a few meters for factory automation, and tens of meters or even longer for autonomous vehicle.

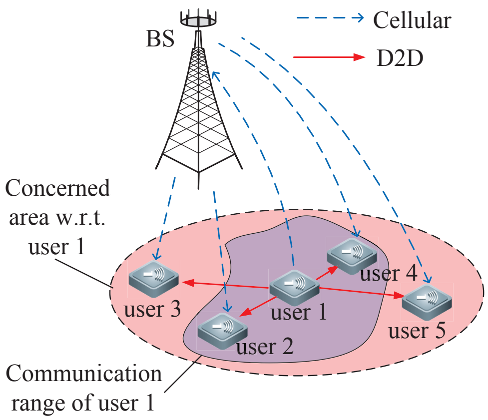


Fig. 1. System model.

A. Three Transmission Modes

To improve reliability, we consider a two-phase transmission protocol. Denote the required total transmission delay of a packet as T, which is divided into two phases with duration T_1 and T_2, respectively. Time is discretized into frames with duration $T_{\rm f}$, which is the minimal time granularity of the system. Therefore, T_1 and T_2 should be divisible by $T_{\rm f}$. To reduce training overhead, we employ broadcast for transmission, and investigate the following three transmission modes.

1) Cellular mode: Each sensor uploads its packet to the BS in the first phase (i.e., uplink). To avoid interference among multiple sensors, we consider frequency division multiple access (FDMA). If the BS successfully receives the packets from multiple sensors, it will broadcast all these packets in the second phase (i.e., downlink). To assist each target receiver to retrieve its interested packets, the BS broadcasts different packets in different frequency and it total transmit power is equally allocated to each packet.

2) D2D mode: Each sensor broadcasts its packet to its target receivers in the first phase, and re-broadcasts the same packet in a different frequency in the second phase to exploit frequency diversity. Again, multiple sensors transmit with FDMA is applied to avoid interference. By setting the duration of one phase as zero, the two-phase transmission protocol can be degenerated into one-phase transmission protocol.

3) Hybrid mode: Each sensor broadcasts a packet to its target receivers and the BS. If the packet is successful received at the BS, the sensor and the BS will re-broadcast the packet in the second phase simultaneously. Otherwise, only the sensor will re-broadcast the packet as in the D2D mode.

B. Path Loss and Shadowing

The maximal communication ranges of the BS and D2D links with ensured QoS and availability, i.e., *the available range*, could be small due to shadowing. Beyond this range, a packet may not be conveyed to all the target receivers with ensured QoS and availability.

The relations between average channel gains and communication ranges can be expressed as [11]

$$\mu^{\rm u} = (r^{\rm u})^{\alpha} + \delta^{\rm u} + \mu_0, \tag{1}$$
$$\mu^{\rm d} = (r^{\rm d})^{\alpha} + \delta^{\rm d} + \mu_0, \tag{2}$$
$$\mu^{\rm m} = (r^{\rm m})^{\alpha} + \delta^{\rm m} + \mu_0, \tag{3}$$

where $\mu^{\rm u}$, $\mu^{\rm d}$, and $\mu^{\rm m}$ are the average channel gains from a sensor to the BS (i.e., uplink), from the BS to the sensor (i.e., downlink) and from the sensor to the target receiver (i.e., D2D link), $r^{\rm u}$, $r^{\rm d}$, and $r^{\rm m}$ are the uplink, downlink and D2D link transmission distance, $\delta^{\rm u}$, $\delta^{\rm d}$ and $\delta^{\rm m}$ are the shadowing of corresponding links, α is the path-loss exponent, and μ_0 is a constant that depends on antenna characteristics.

To increase the available range, we are interested in cases where the distances between the users and BS are large (i.e., larger than the decorrelation distance of shadowing). Hence, it is reasonable to assume that $\delta^{\rm u}$ and $\delta^{\rm m}$ are independent. A sensor and its target receivers could be closely located. Therefore, the shadowing of uplink and downlink is highly correlated, and we assume that $\delta^{\rm u}$ and $\delta^{\rm d}$ are identical.

III. Transmission Error Probability and Reliability

Reliability is defined as the probability that a packet can be successfully received at a target receiver. We first derive the transmission error probability of each link and then derive the overall packet loss probability, i.e., reliability.

A. Transmission Error Probability

Assume that each packet is transmitted over a flat fading channel with bandwidth W. The transmission durations in two phases are shorter than the channel coherence time since delay requirement is extremely short [1]. Since broadcast is considered in this work, channel state information (CSI) is not available at the transmitters. By sending pilots, CSI is available at the receivers.

With short transmission duration, the blocklength of channel codes is finite. According to [5], the uplink achievable rate in finite blocklength regime can be expressed as follows,

$$R \approx \frac{T_1 W}{\ln 2}\left[\ln\left(1+\frac{\mu^{\rm u} P_{\rm t}^{\rm m} g^{\rm u}}{N_0 W}\right) - \sqrt{\frac{V}{T_1 W}} f_{\rm Q}^{-1}\left(\varepsilon^{\rm u}\right)\right], \tag{4}$$

where $P_{\rm t}^{\rm m}$ is the transmit power of a sensor, N_0 is the single-side noise spectral density, $g^{\rm u}$ is the normalized instantaneous channel gain, $f_{\rm Q}^{-1}(.)$ is the inverse of Q-function, $\varepsilon^{\rm u}$ is the uplink transmission error probability, $V = 1 - \frac{1}{\left(1+\frac{\mu^{\rm u} g^{\rm u} P_{\rm t}^{\rm m}}{N_0 W}\right)^2}$.

In the first phase of the cellular mode, the transmission error probability to convey a packet containing b bits from a sensor to the BS in finite blocklength regime can be obtained from (4) by setting $R=b$, i.e.,

$$\varepsilon^{\mathrm{u}} \approx \mathbb{E}_g \left\{ f_{\mathrm{Q}} \left(\sqrt{\frac{T_1 W}{V}} \left[\ln\left(1+\frac{\mu^{\mathrm{u}} g^{\mathrm{u}} P_{\mathrm{t}}^{\mathrm{m}}}{N_0 W}\right) - \frac{b \ln 2}{T_1 W} \right] \right) \right\}, \tag{5}$$

where the average is taken over instantaneous channel gain.

Similarly, in the first phase of the D2D mode the transmission error probability $\varepsilon_1^{\mathrm{m}}$ can be obtained by replacing u^{u} and g^{u} in (5) with u^{m} and g^{m}, where g^{m} is the normalized instantaneous channel gain of the D2D link.

In the second phase, the received signal power at a target receiver may include two parts. The first part comes from the sensor, and the second part may come from the BS depending on whether the BS decodes the packet successfully or not in the first phase. If the BS decodes the packet successfully, the transmission error probability can be expressed as follows,

$$\varepsilon^{\mathrm{d}} \approx \mathbb{E}_g \left\{ f_{\mathrm{Q}} \left(\frac{\ln\left(1+\frac{\mu^{\mathrm{m}} g^{\mathrm{m}} P_{\mathrm{t}}^{\mathrm{m}} + \mu^{\mathrm{d}} g^{\mathrm{d}} P_{\mathrm{t}}^{\mathrm{d}}/N_{\mathrm{t}}}{N_0 W}\right) - \frac{b \ln 2}{T_2 W}}{\sqrt{V/\left(T_2 W\right)}} \right) \right\}, \tag{6}$$

where $P_{\mathrm{t}}^{\mathrm{d}}$ is the transmit power at the BS, and g^{d} is the normalized instantaneous channel gain from the BS to a target user. Since CSI is not available at the BS, the transmit power is equally allocated to N_{t} antennas. If the packet is not successfully decoded by the BS in the first phase, then by substituting $P_{\mathrm{t}}^{\mathrm{d}}=0$ into (6), we can obtain the transmission error probability in the second phase of the D2D link, which is denoted as $\varepsilon_2^{\mathrm{m}}$.

B. Packet Loss Probability

For the hybrid mode, a packet is lost in two cases. If the D2D transmission in the first phase fails but the packet is successfully received at the BS, then the packet will be lost if it is not successfully conveyed to the target receiver via downlink broadcast in the second phase. The probability that this case happens is $\varepsilon_1^{\mathrm{m}}(1-\varepsilon^{\mathrm{u}})\varepsilon^{\mathrm{d}}$[1]. If both the D2D and uplink transmissions fail in the first phase, then the packet will be lost if the D2D transmission in the second phase also fails. The probability that this case happens is $\varepsilon_1^{\mathrm{m}}\varepsilon^{\mathrm{u}}\varepsilon_2^{\mathrm{m}}$. Since the two cases are mutual exclusive, the packet loss probability of the hybrid mode is the sum of these two parts, i.e.,

$$P_l^{\mathrm{hyb}} = \varepsilon_1^{\mathrm{m}}(1-\varepsilon^{\mathrm{u}})\varepsilon^{\mathrm{d}} + \varepsilon_1^{\mathrm{m}}\varepsilon^{\mathrm{u}}\varepsilon_2^{\mathrm{m}}. \tag{7}$$

For the cellular mode, where $\varepsilon_1^{\mathrm{m}}=\varepsilon_2^{\mathrm{m}}=1$, the packet loss probability can be bounded by $P_l^{\mathrm{ud}} = \varepsilon^{\mathrm{u}}+\varepsilon^{\mathrm{d}}-\varepsilon^{\mathrm{u}}\varepsilon^{\mathrm{d}} \le \varepsilon^{\mathrm{u}}+\varepsilon^{\mathrm{d}}$.

For the D2D mode, where $\varepsilon^{\mathrm{u}}=\varepsilon^{\mathrm{d}}=1$, the packet loss probability is $P_l^{\mathrm{mm}} = \varepsilon_1^{\mathrm{m}}\varepsilon_2^{\mathrm{m}}$.

From P_l^{hyb}, P_l^{ud} and P_l^{mm}, we have

$$P_l^{\mathrm{hyb}} \le \min\{P_l^{\mathrm{ud}}, P_l^{\mathrm{mm}}\}. \tag{8}$$

[1]The probability is correct when $\varepsilon_1^{\mathrm{m}}$, ε^{u} and ε^{d} are independent. However, shadowing of these links can be correlated. To apply it, we fix shadowing of the links as the worst case. Then, $\varepsilon_1^{\mathrm{m}}$, ε^{u} and ε^{d} only depend on small-scale fadings of related links, and hence are independent.

In cases without specification of any transmission mode, we use P_l to represent packet loss probability.

IV. Improving Available Ranges

A. Problem Formulation

The network availability is defined as the probability that the E2E delay (i.e., the total transmission time in this work) is less than T and the packet loss probability is lower than the required maximal packet loss probability, i.e., $P_l \le \varepsilon_{\max}$ [2]. Denote the requirement on network availability as P_{A}. To guarantee the requirement, $\Pr\{P_l \le \varepsilon_{\max}\} \ge P_{\mathrm{A}}$ should be satisfied. In this work, we aim to maximize the available ranges, within which the QoS and availability can be satisfied. To this end, we maximize the minimal average channel gains of both uplink and downlink in the cellular mode and the minimal average channel gain of the D2D link in the D2D mode, i.e., considering the worst case distance and shadowing.

It can be noted that (8) shows that a packet can be successfully transmitted with hybrid mode if either the cellular mode or D2D mode works. Based on this observation, we consider the worst case of shadowing, i.e., $\Pr\{\delta^{\mathrm{u}} < \delta_{\mathrm{C}}^{\mathrm{hyb}}\}\Pr\{\delta^{\mathrm{m}} < \delta_{\mathrm{D}}^{\mathrm{hyb}}\} = 1-P_{\mathrm{A}}$, where $\delta_{\mathrm{C}}^{\mathrm{hyb}}$ and $\delta_{\mathrm{D}}^{\mathrm{hyb}}$ is the shadowing of cellular link and D2D link, respectively.

For cellular mode and D2D mode, to satisfy network availability, we also consider the worst case of shadowing such that $\Pr\{\delta^{\mathrm{u}} \ge \delta_{\mathrm{C}}\} = P_{\mathrm{A}}$ and $\Pr\{\delta^{\mathrm{m}} \ge \delta_{\mathrm{D}}\} = P_{\mathrm{A}}$, where δ_{C} and δ_{D} is the shadowing of cellular mode and D2D mode.

Since shadowing is fixed, maximizing available range is equivalent to minimizing average channel gain. The optimization problem that minimizing μ^{u} can be expressed as follows,

$$\min_{T_1, T_2, \mu^{\mathrm{u}}} \quad \mu^{\mathrm{u}} \tag{9}$$

$$\text{s.t.} \quad P_l \le \varepsilon_{\max}, \tag{9a}$$

$$T_1 + T_2 = T. \tag{9b}$$

Constraint (9a) and (9b) ensures reliability and delay requirement, respectively. Similarly, the optimization problem that minimizing μ^{m} can be expressed as follows,

$$\min_{T_1, T_2, \mu^{\mathrm{m}}} \quad \mu^{\mathrm{m}} \quad \text{s.t.} \quad \text{(9a)}, \text{(9b)}. \tag{10}$$

B. Global Optimal Solutions

It is not hard to show that P_l of the three transmission modes are non-convex in T_1, T_2 and average channel gains. As a result, problem (9) and problem (10) are non-convex. To find the global optimal solutions, we need some properties.

First, we can obtain a property of transmission error probabilities (See Appendix A.).

Property 1. Transmission error probabilities ε^{u}, $\varepsilon_1^{\mathrm{m}}$, $\varepsilon_2^{\mathrm{m}}$, and ε^{d} decrease with the average channel gains μ^{u} and μ^{m} and the transmission durations T_1 and T_2.

By substituting transmission error probabilities into (7), the packet loss probability is a function with respect to μ^{u}, μ^{m},

T_1 and T_2. Based on Property 1, we can obtain the Property of packet loss probability (See Appendix B.).

Property 2. P_l decreases with $\mu^{\rm u}$ and $\mu^{\rm m}$.

Given $\mu^{\rm u}$ and $\mu^{\rm m}$, by optimizing T_1 and T_2 we can minimize the packet loss probability from the following problem,

$$\min_{T_1,T_2} \quad P_l \qquad (11)$$
$$\text{s.t.} \quad \text{(9b)}.$$

Denote the minimal packet loss probability as $P_l^*(\mu^{\rm u}, \mu^{\rm m})$. By comparing $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ with $\varepsilon_{\max}$, we can see whether the service is available or not with $\mu^{\rm u}$ and $\mu^{\rm m}$. Since T_1 and T_2 should be divisible by $T_{\rm f}$, the feasible solution of problem (11) is finite and it is not hard to obtain $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ with exhaustive search method.

According to Property 2, we can obtain a property of $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ as follows (See Appendix C.),

Property 3. $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ decreases with $\mu^{\rm u}$ and $\mu^{\rm m}$.

Since $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ decreases with $\mu^{\rm u}$, to obtain the minimal $\mu^{\rm u}$ of problem (9), we need to find the minimal $\mu^{\rm u}$ that makes problem (9) feasible. According to Property 3, we can use the binary search method to find $\mu^{{\rm u}^*}$ that satisfies $P_l^*(\mu^{{\rm u}^*}, \mu^{\rm m}) = \varepsilon_{\max}$ with given $\mu^{\rm m}$. Similarly, with given $\mu^{\rm u}$ we can also find $\mu^{{\rm m}^*}$ that satisfies $P_l^*(\mu^{\rm u}, \mu^{{\rm m}^*}) = \varepsilon_{\max}$.

Given the required packet loss probability $\varepsilon_{\max}$, we can directly obtain the following proposition from Property 3.

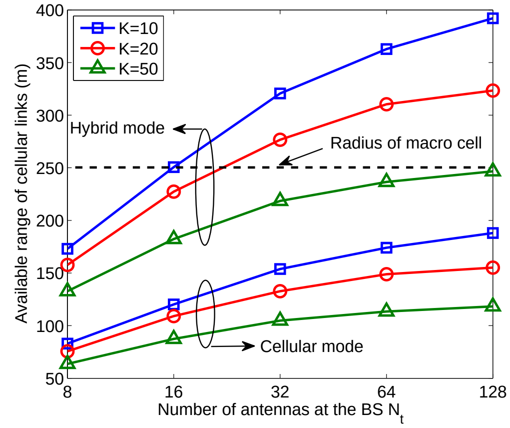
Proposition 1. There is a tradeoff between the available range of cellular links and that of D2D links.

V. Numerical Results

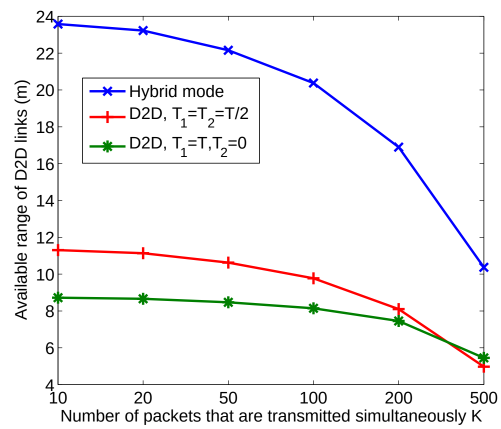
In this section, we consider the worst case that the distance between BS and the target receivers or the distance between sensor and its receivers equals to the available range. Denote the number of sensors as K. The total bandwidth is equally allocated to each sensor. Frequency-hopping is applied in the two phases of D2D transmission to exploit frequency diversity. Parameters are listed in Table I, unless otherwise specified.

TABLE I
PARAMETERS [1, 12]

Required packet loss probability $\varepsilon_{\max}$	10^{-7}
Delay requirement T	1 ms
Network availability requirement $P_{\rm A}$	99.999 %
Duration of each frame $T_{\rm f}$	0.1 ms
Inter-site distance in urban areas	500 m
Total bandwidth	20 MHz
Total transmit power of the BS	46 dBm
Transmit power of each sensor	23 dBm
Single-sided noise spectral density N_0	-173 dBm/Hz
Packet size u	20 bytes
Path loss model	$35.3 + 37.6\lg(d)$
Standard variance of shadowing	8 dB



(a) Available range of the BS v.s. the number of antennas.



(b) Available range of D2D link v.s. the number of sensors.

Fig. 2. Available ranges of different links, where $\delta_{\rm C}^{\rm hyb} = \delta_{\rm D}^{\rm hyb}$ and $\Pr\{\delta^{\rm u} < \delta_{\rm C}^{\rm hyb}\}\Pr\{\delta^{\rm m} < \delta_{\rm D}^{\rm hyb}\} = 1 - P_{\rm A}$.

The available range with different transmission modes are illustrated in Fig. 2. By setting $\delta_{\rm C}^{\rm hyb} = \delta_{\rm D}^{\rm hyb}$, the availability of cellular transmission and D2D transmission are equal.[2] Results in Fig. 2(a) show that with cellular mode, the available range of BS is less than the radius of macro cell even when $N_{\rm t}$ is large and K is small (e.g., $N_{\rm t} = 128$ and $K = 10$). The results in Fig. 2(b) show that the available range with D2D mode is around 10 m. If the concerned areas is larger than the available range, then the network availability cannot be satisfied. Besides, with retransmission the D2D communication range is longer than that without retransmission in most cases, unless the bandwidth for each packet is small (i.e., when $K = 500$, the bandwidth for each packet is 40 kHz). Moreover, when the available range of the BS is longer than the radius of each cell with hybrid mode, the QoS requirement can be satisfied for any pair of sensor and receiver that with distance is shorter than the available range of D2D link in Fig. 2(b). For example, with hybrid mode, when $K = 20$, the available range of the BS is longer than 250 m with 32 antennas. Meanwhile, the available range of D2D links is around 23 m, which is doubled when

[2]As will be shown in Fig. 3, by adjusting the values of $\delta_{\rm C}^{\rm hyb}$ and $\delta_{\rm D}^{\rm hyb}$, we can trade available range of D2D link with available range of the BS.

compared with D2D mode.

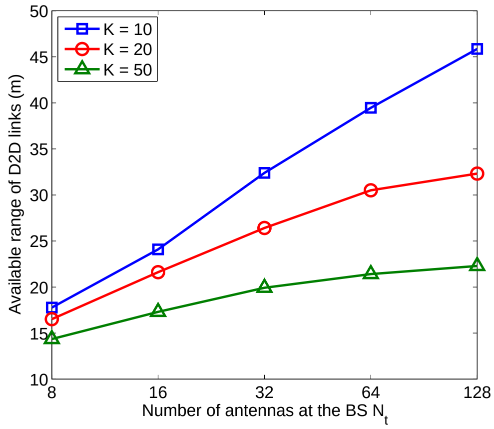


Fig. 3. Available range of D2D links with hybrid mode v.s. the number of antennas at the BS, where the available range of BS is set to be 250 m.

Since the radius of each cell is 250 m [1], it is not necessary to support an available range that is longer than the radius of each cell. As shown in Proposition 1, we can trade available range of D2D links with available range of BS. By reducing the communication range of the BS, the QoS requirement with cellular link can be satisfied with smaller $\delta_{\rm C}^{\rm hyb}$. Then, the required $\delta_{\rm D}^{\rm hyb}$ to guarantee $\Pr\{\delta^{\rm u} < \delta_{\rm C}^{\rm hyb}\}\Pr\{\delta^{\rm m} < \delta_{\rm D}^{\rm hyb}\} = 1 - P_{\rm A}$ increases. As a result, the D2D communication range increases. As shown in Fig. 3, with hybrid mode the available range of D2D links increases the antennas at the BS.

VI. Conclusion

In this work, we obtained the available ranges of cellular and D2D links for URLLC with different transmission modes. Two optimization problems were formulated to maximize the available range of cellular links or that of D2D links. Analysis results indicated that there is a tradeoff between the available range of cellular links and that of D2D links. Numerical results showed that with the hybrid mode, the available ranges of cellular and D2D links can be doubled. Moreover, by setting the available range of the cellular links equal to the radius of each cell, the available range of D2D links increases with the number of antennas at the BS.

Appendix A
Proof of Property 1

Proof. To prove the property, we take $\varepsilon^{\rm u}$ in (5) as an example. For other transmission error probabilities, the proofs are similar, and hence are omitted.

Since $\sqrt{\frac{T_1 W}{V}}\left[\ln\left(1+\frac{\mu^{\rm u} g^{\rm u} P_{\rm m}}{N_0 W}\right) - \frac{b\ln 2}{T_1 W}\right]$ increases with $\mu^{\rm u}$, and $f_{\rm Q}(x)$ is a decreasing function, $\varepsilon^{\rm u}$ decreases with $\mu^{\rm u}$. The relation between $\varepsilon^{\rm u}$ and T_1 in (5) can be re-expressed as $\varepsilon^{\rm u} \approx \mathbb{E}_g\left\{f_{\rm Q}\left(c_1\sqrt{T_1} - \frac{c_2}{\sqrt{T_1}}\right)\right\}$, where c_1 and c_2 are positive parameters that do not depend on T_1. It is not hard to prove that $c_1\sqrt{T_1} - \frac{c_2}{\sqrt{T_1}}$ increases with T_1. $f_{\rm Q}(x)$ decreases with x, and hence $\varepsilon^{\rm u}$ decreases with T_1. The proof follows. □

Appendix B
Proof of Property 2

Proof. We only take $P_l^{\rm hyb}$ for example. For other transmission modes, the proofs are similar. From (7), we have $P_l^{\rm hyb}$ increases with $\varepsilon_1^{\rm m}$ and $\varepsilon_2^{\rm m}$, and hence it decreases with $\mu^{\rm m}$ according to Property 1. The expression in (7) can be re-expressed as $P_l^{\rm hyb} = \varepsilon_1^{\rm m}\varepsilon^{\rm d} + \varepsilon_1^{\rm m}\varepsilon^{\rm u}(\varepsilon_2^{\rm m} - \varepsilon^{\rm d})$, where $\varepsilon_2^{\rm m}$ is obtained by substituting $P_{\rm t}^{\rm d} = 0$ into $\varepsilon^{\rm d}$ in (6). Thus, $\varepsilon_2^{\rm m} - \varepsilon^{\rm d} > 0$. Therefore, $P_l^{\rm hyb}$ increases with $\varepsilon^{\rm u}$, and hence it decreases with $\mu^{\rm u}$. This completes the proof. □

Appendix C
Proof of Property 3

Proof. Similar to Appendix B, we take $P_l^{\rm hyb}$ for example. For notational simplicity, we omit index hyb in this appendix. Consider two different average channel gains from sensor to the BS, i.e., $\hat{\mu}^{\rm u} < \tilde{\mu}^{\rm u}$. The related optimal solution of problem (11) is $\{\hat{T}_1, \hat{T}_2\}$ and $\{\tilde{T}_1, \tilde{T}_2\}$, respectively. According to Property 2, we have

$$P_l(\hat{\mu}^{\rm u}, \mu^{\rm m}, \hat{T}_1, \hat{T}_2) > P_l(\tilde{\mu}^{\rm u}, \mu^{\rm m}, \hat{T}_1, \hat{T}_2). \qquad \text{(C.1)}$$

Moreover, $\{\tilde{T}_1, \tilde{T}_2\}$ is the optimal solution that minimizes $P_l(\tilde{\mu}^{\rm u}, \mu^{\rm m}, T_1, T_2)$, which means

$$P_l(\tilde{\mu}^{\rm u}, \mu^{\rm m}, \hat{T}_1, \hat{T}_2) > P_l(\tilde{\mu}^{\rm u}, \mu^{\rm m}, \tilde{T}_1, \tilde{T}_2). \qquad \text{(C.2)}$$

From (C.1) and (C.2), we have $P_l^*(\hat{\mu}^{\rm u}, \mu^{\rm m}) > P_l^*(\tilde{\mu}^{\rm u}, \mu^{\rm m})$. Therefore, $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ decreases with $\mu^{\rm u}$. Similarly, we can also prove that $P_l^*(\mu^{\rm u}, \mu^{\rm m})$ decreases with $\mu^{\rm m}$. The proof follows. □

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