Abstract—In this work, we analytically study the performance of an in-band and self-fronthauling millimeter-wave Cloud-Radio Access Network (C-RAN). By considering a stochastic-geometry approach for the modeling of the position and number of Baseband Units (BBUs), Remote Radio Heads (RRHs), and mobile terminals (MTs), we provide the following three-fold contribution: i) We derive an analytical framework for the MT rate distribution for two types of wireless RRHs, namely half-duplex (HD) and full-duplex (FD); ii) Based on the derived framework, we prove that the maximum performance gain of the FD network over its HD counterpart is achieved for a substantially higher density of the wireless RRHs compared to the fiber-connected ones and an adequately small self-interference power level; iii) Finally, we compute an analytical expression of the total cost required to increase the density of the fiber-connected RRHs in a city that showcases the tradeoff between their density increase and the incurred cost. The aforementioned system-level trends are validated by means of Monte Carlo simulations.

Index Terms—Cloud-RAN, millimeter-wave networks, self-fronthauling, half-duplex, full-duplex.

I. INTRODUCTION

A. Background

O

VER the last years, there has been a continuous increase in the demand for higher rates owing to the proliferation of smartphone devices. According to the overwhelming figures, by 2022 global mobile data traffic is expected to reach a monthly run of around 77 exabytes per year, which corresponds to a higher than a 6-fold growth with respect to the monthly run of 2017 [1]. Obviously, such demands cannot be accommodated by the current cellular standards that rely on sub-6 GHz bands to convey information, such as the Long-Term Evolution Advanced, which can offer a peak-data rate slightly above 1 Gbps [2]. As a result, the future of the substantially congested sub-6 GHz bands that are used for communication is highly uncertain. Due to this, two important features of the forthcoming 5G technology that have been proposed to meet the ever-increasing rate demands have been [3]: i) The migration to higher than 6 GHz frequency bands due to the availability of a significantly higher bandwidth. Such an availability directly translates to higher rates according to Shannon’s capacity formula; ii) Extreme small-cell densification to improve spectral efficiency.

Regarding the use of above-6 GHz bands for communication, there has been a substantial research over the recent years regarding the potential of cellular communications at the millimeter-wave (mmWave) spectrum that spans the range 30-100 GHz. As far as works that showcase such a potential are concerned, outdoor and indoor channel models have been developed that apply to carrier frequencies which exhibit a relatively small atmospheric absorption, such as the 28 and 73 GHz bands [4], [5]. According to these works, both coverage-probability and average-rate gains can be achieved compared to sub-6 GHz networks, as the density of the cells increases and for highly-directional antennas employed at both the cells and MTs. In addition, outdoor measurements in urban scenarios indicate that distances between a MT and its associated cell smaller than 200 m are needed so that outage-free communication is achieved [4]. Hence, the migration to the mmWave bands is essential to be combined with cell densification in order to leverage the substantially higher available bandwidth [6]. Regarding this, by using a stochastic geometry approach where the cells on the plane are modeled as points of a Poisson point process (PPP)1 in [14] the authors show that although for an average cell radius of 200 m (small cell density) a network in the 2.5 GHz band outperforms a mmWave network operating at 28 and 73 GHz bands, the opposite holds for an average cell radii of 100 m and 50 m (high cell density). In addition, the significant performance enhancement achieved by mmWave networks under a high-cell densification is also demonstrated in [17] by again modeling the position and number of cells on the plane according to a PPP, as in [14].

The aforementioned works on mmWave networks that demonstrate the significant gains achieved as the cell density

1Such a stochastic geometry approach where nodes on the plane such as base stations, small cells, relays, and MTs are modeled according to PPPs is a convenient tool for tractable system-level analysis and has been applied to different scenarios of interest, such as the modeling and analysis of downlink [7]–[9], multi-antenna [10], [11], heterogeneous [12]–[14], uplink [15], [16], mmWave [14], [17], [18] and full-duplex (FD) cellular networks [19], [20], to mention some indicative examples.
According to the C-RAN architecture, the baseband processing recently proposed architecture for future 5G networks [27]. Fronthauling is inextricably linked to the Cloud network, whereas the fronthaul network to the connections between the BBUs and the core network [22]–[26] (and references therein). Apart from the importance of the backhaul network for meeting the foreseen rates of 5G cellular networks, over the recent years the notion of fronthauling has gained equal importance. Fronthauling is inextricably linked to the Cloud Radio-Acces Network (C-RAN) architecture, which is a recently proposed architecture for future 5G networks [27]. According to the C-RAN architecture, the baseband processing is detached from the already existing entities that are called base stations and allocated to particular units that are called Baseband Units (BBUs). BBUs are connected to nodes called Remote Radio Heads (RRHs) that contain the RF equipment and antennas needed for transmission and reception to/from the MTs. Hence, in such an architecture the backhaul network corresponds to the connections between the BBUs and the core network, whereas the fronthaul network to the connections between the BBUs and the RRHs. These fronthaul links should be ideally based on fiber cables for optimal performance. However, similarly to the aforementioned deployment issues that make self backhauling a more attractive option for the backhaul network, self fronthauling where a number of RRHs are fronthauled wirelessly through fiber-connected RRHs is a favorable approach for vendors [28]. To the best of our knowledge, only [29] and [30] study sub-6 GHz C-RAN architectures that consider wireless fronthauling. In particular, in [29] the authors consider a single-cell architecture where a BBU controls a number of RRHs via wireless fronthaul links. For RRHs acting as either decode-and-forward (DF) or decompress-and-forward relays, the authors consider the problem of jointly optimizing the BBU and RRH operations with the goal of maximizing the weighted sum rate subject to BBU and per-RRH power constraints. In [30], the authors consider an out-of-band multicllustering architecture, where each BBU communicates with each associated RRHs wirelessly, and jointly optimize the fronthaul and access links with the goal of maximizing the sum rate of all the MTs.

Consequently, the system-level analysis of a self-fronthauling mmWave C-RAN architecture is a largely unexplored area, which requires contributions due to the practical importance of including wireless fronthaul links apart from cable ones, as aforementioned.

B. Contribution

Motivated by the importance of C-RAN architectures for the forthcoming 5G networks and the practical need for self-fronthauling in such architectures, in this work we consider the system-level analysis of a self-fronthauling in-band architecture where the same mmWave band is used for the fronthaul and access wireless links. Our contribution can be summarized as follows:

- We develop a stochastic-geometry based system-level analytical framework for the distribution of the downlink MT rate, which we denote by coverage rate. The framework is flexible enough by including as parameters the densities of the wired and wireless RRHs together with the user load. Consequently, it can be used to estimate the performance for any ratio of the fiber-connected RRHs over the wireless ones. In addition, the framework incorporates two possibilities for the type of wireless RRHs, namely half-duplex (HD) and full-duplex (FD). In the HD approach, the wireless RRHs receive and transmit in different time slots, whereas in its FD counterpart simultaneous reception and transmission at those nodes occurs. Simulation results reveal that there is a close match between the simulations and the analysis, which validates the developed framework.

- Apart from its close match with the simulations, the analytical framework reveals that the highest rate gain of the FD case over the HD one is achieved for a wireless-RRH density substantially higher than the one of the fiber-connected RRHs and for a substantially small self-interference power level caused by the simultaneous transmission and reception of the wireless RRHs in the FD case. However, as the power level of the self-interference increases, these gains diminish. These trends are validated by the simulation results.

- Finally, by parameterizing the possible cost per meter involved in the design and installation of fiber cables, we show that as the density of the fiber-connected RRHs increases, the involved cost substantially increases as well for indicative large cities, in terms of area, in the world. This is an important tradeoff to be taken into account by the system designer since the important rate increase achieved by increasing the ratio of the fiber-connected
RRHs over the wireless ones requires notable investments regarding the fiber network.

Organization: The rest of this paper is organized as follows: In Section II, we present the considered scenario together with the main assumptions. In Section III, for both the HD and FD cases we firstly present the signal model, subsequently we formulate the instantaneous signal-to-interference plus noise ratio (SINR) expressions according to our signal model and, finally, based on these expressions we formulate the MT coverage rate as the examined metric. In Section IV, we derive the analytical framework of the coverage rate, use it to extract insights regarding the comparison of the HD and FD cases, and present an expression for the total cost involved for increasing the density of the fiber-connected RRHs in a city. In Section V, the analytical model and the extracted insights are validated by means of Monte-Carlo simulations. Finally, Section VI concludes this work.

II. SYSTEM MODEL

In this section, we first present the scenario under consideration and, subsequently, we proceed with the assumptions.

A. Scenario

We assume a C-RAN architecture where the deployed RRHs are associated with BBUs in which the baseband processing is taking place. In addition, we consider that the number and position of RRHs and BBUs are described by two uniformly distributed PPPs on \( \mathbb{R}^2 \), namely \( \Phi_R \) and \( \Phi_{BBU} \), with intensities \( \lambda_R \) and \( \lambda_{BBU} \), respectively. As aforementioned in Section I, due to the high deployment and leasing costs involved with fiber connections in practical cases it is expected that only a portion of the deployed RRHs are going to have fiber connection towards their associated BBUs. The rest of RRHs are going to be wirelessly connected to their associated BBUs through the fiber-connected RRHs in a two-hop architecture. Based on this, we assume that the fiber-connected RRHs are described by the PPP process \( \Phi^{(C)}_R \) with intensity \( \lambda^{(C)}_R \) and the wirelessly connected ones by the PPP process \( \Phi^{(W)}_R \) with intensity \( \lambda^{(W)}_R \). Consequently, it holds that \( \Phi_R = \Phi_{C}^{(R)} \cup \Phi^{(W)}_R \) and \( \lambda_R = \lambda^{(C)}_R + \lambda^{(W)}_R \). Finally, we assume that the MTs are also described by a uniform PPP, denoted by \( \Phi_{MT} \), with intensity \( \lambda_{MT} \). A snapshot of such a proposed architecture is depicted in Fig. 1.

Moreover, we denote a particular target MT by \( MT_s \). If \( MT_s \) is served through a one-hop transmission, the serving fiber-connected RRH is denoted by \( R^{(C)}_o \). On the other hand, if \( MT_s \) is served through a two-hop transmission, the wireless RRH that serves it is denoted by \( R^{(W)}_o \) and the fiber-connected RRH that serves \( R^{(W)}_o \) is denoted by \( R^{(C)}_o \). Without loss of generality and based on the Slivnyak theorem [31, vol. 1, Th. 1.4.5], in this work we study the performance metrics of a \( MT_s \) located at the origin of the bi-dimensional plane.

B. Assumptions

1) Blockage Modeling: Similar to [32], for the blockages that may exist in the radio path (such as buildings) we consider that they are described by a Boolean scheme of circles on \( \mathbb{R}^2 \). According to this assumption, the centers of the blockages form a homogeneous PPP \( \Phi_{Blockages} \) of intensity \( \lambda_{Blockages} \). In addition, for simplicity we assume that the radius of all the blockages is equal to \( R_B \).

By denoting by \( K_i \) the number of blockages in a random link \( i \) between two RRHs or between a RRHs and a MT and by \( R_i \) the length of the link, it is proved in [33] and [34] that \( K_i \) is a Poisson random variable with expected value equal to \( \beta R_i \). Regarding \( \beta \), it holds that \( \beta = \frac{\rho ln(1+\rho)}{\pi A} \), where \( \rho = 2\pi R_B^2 \) and \( A = \pi R_B^2 \) are the perimeter and area of the buildings, respectively, and \( p = \lambda_{Blockages} \pi R_B^2 \), with \( 0 < p < 1 \), is the percentage of the area occupied by blockages. In addition, the probability that the link \( i \) does not contain any blockage, which we denote by \( Pr \{ K_i = 0 \} \), is given by

\[
Pr \{ K_i = 0 \} = \exp(-\beta R_i).
\]

Finally, for analytical tractability we assume that the number of blockages in any two links from two RRHs to a RRH or MT are independent. This means that the same blockage cannot be in the radio path of more than one link between two nodes. According to [33], such a simplification causes a minor loss in accuracy when the size of the blockages is relatively small.

2) Node Association, Path Loss, Channel Characteristics, and Access Protocol:

a) RRH and MT Association: We assume that: i) Each wireless RRH is associated with the wired RRH from which it receives the strongest signal; ii) Each MT is associated with the RRH, wired or wireless, from which it receives the strongest signal; iii) Each wired RRH is associated with the closest BBU.

b) Path Loss: Let us assume that the link \( i \) between two nodes in the network is denoted by \( R_i \). The resulting large-scale path loss in the case of outdoor LOS or NLOS link, which we denote by \( l^{(m)}_{s,i} \), is given by

\[
l^{(m)}_{s,i}(R_i) = k_0(R_i)^{\alpha^{(m)}_s},
\]

where \( m \in \{\{R^{(C)},R^{(W)}\}, \{R^{(W)},R^{(W)}\}, \{R^{(C)},MT\}, \{R^{(W)},MT\}\} \) is the index representing the link between a fiber-connected and a wireless RRH, two wireless RRHs, a fiber-connected RRH and a MT, and, finally, a wireless RRH and a MT, respectively, \( s_i \in \{LOS,NLOS\} \), and \( \alpha^{(m)}_s \),
Power level, denoted by \( P \), is subject to additive white Gaussian noise. Its possibility of having different path-loss exponents for the free-space path loss at a distance of 1 m.

c) Frequency Band of Operation: We consider the 28 GHz mmWave band for operation. Such a band has been considered in several literature works on mmWave networks due to the relatively small atmospheric absorption that it exhibits [4], [6], [17].

d) Propagation Conditions: We assume that the outdoor mmWave communication can occur in line-of-sight (LOS) and non-LOS (NLOS) conditions, which is supported by reported measurements [5], [14].

e) Shadowing: For analytical tractability, we assume that the possible shadowing effects are incorporated into the blockage model, as it is assumed in [35].

f) Fast Fading: According to measurements, in mmWave bands fast fading has a less pronounced effect than the sub-6 GHz bands [36], where it is common that fast fading is modeled as a Rayleigh variable. However, due to the fact that modeling fast fading with a more flexible distribution, such as the Nakagami distribution, is not expected to provide additional insights regarding the system design, in this work we assume that the fast fading processes corresponding to the links between RRHs and MTs simply follow a Rayleigh distribution originating from a complex Gaussian process with zero mean and unit variance. On the other hand, for the connections among RRHs we logically assume that there is no fast-fading effect due to their fixed position. Finally, with \( h_{x,y} \) we denote the Gaussian complex envelope corresponding to the fast-fading process regarding the link between the nodes \( X \) and \( Y \).

g) Noise at the Receiver: We assume that the received signal is subject to additive white Gaussian noise. Its power level, denoted by \( \sigma_{n}^2 \), in dBm is equal to \(-174 + 10 \log_{10}(BW) + F_{db} \), where \( F_{db} \) is the noise figure in dB and \( BW \) is the transmission bandwidth.

h) Access Protocol: We consider a time-division multiple access (TDMA) protocol, which means that only one MT per RRH is served in each time slot to which the whole available bandwidth is given. The TDMA consideration arises from the fact that a frequency-division multiple access approach would require multiple radio-frequency channels per RRH. This can create important wide-scale deployment issues due to the high cost and power consumption associated with mixed-signal circuits at mmWave bands [37]. Due to this, the TDMA protocol that requires only one RF chain per RRH has been proposed as a more affordable approach for future mmWave networks [38], which is the reason for its adoption in this work.

Based on this, all the RRHs other than the serving RRH that concurrently transmit are interferers towards the reference MT.

3) Antenna Gains and Beamsteering:

a) Antenna gains of the RRHs and MTs: We assume that antenna arrays are deployed at the RRHs and MTs in order to enable beamsteering. Their gains are given by a sectored radiation pattern as [17]

\[
G_q(\theta) = \begin{cases} 
G_{q}^{(\text{max})}, & |\theta| \leq \theta_q \\
G_{q}^{(\text{min})}, & |\theta| > \theta_q
\end{cases}
\]

where \( q \in \{R^{(C)}, R^{(W)}_R, R^{(W)}_T, MT\} \), in the case of the transmit array of fiber-connected RRHs, the receive array of wireless RRHs, the transmit array of wireless RRHs, and the receive array of MTs, respectively. In addition, \( \theta \in [-\pi, \pi] \) is the angle off the antenna boresight direction, \( \theta_q \) is the half-power beamwidth of the main lobe, and \( G_{q}^{(\text{max})} \) and \( G_{q}^{(\text{min})} \) are the maximum and minimum antenna gains, respectively. Hence, as it is also assumed in [17], with such modeling we consider for simplicity that the array gains are constant and equal to \( G_{q}^{(\text{max})} \) and \( G_{q}^{(\text{min})} \) for all angles in the main lobe and side lobes, respectively.

b) Beamsteering: We assume that prior to data transmission the transmit and receive nodes of interest steer the orientation of their antennas in a way that the maximum directivity gain, i.e. \( G_{q_1}^{(\text{max})} \) \( G_{q_2}^{(\text{max})} \), where \( q_1 = \{R^{(C)}, R^{(W)}_R\} \) and \( q_2 = \{R^{(W)}_T, MT\} \), is achieved. This can be realized by the existence of a feedback channel and the dispatch of pilot signals from the MT/RRH to the serving RRH prior to data transmission. Since the beams of the interfering links are uniformly distributed in \([-\pi, \pi]\), there are four possible values of the directivity gain between a RRH interferer and the MT/RRH of interest, i.e. \( G_{q_1}^{(\text{max})} G_{q_2}^{(\text{max})} \), \( G_{q_1}^{(\text{max})} G_{q_2}^{(\text{min})} \), \( G_{q_1}^{(\text{min})} G_{q_2}^{(\text{max})} \), and \( G_{q_1}^{(\text{min})} G_{q_2}^{(\text{min})} \) with respective probabilities given in Table I.

\[
\begin{align*}
&F_{R_1} = \frac{\theta_1}{2\pi} & &F_{R_2} = \frac{\theta_2}{2\pi} & &F_{R_3} = \frac{\theta_3}{2\pi} & &F_{R_4} = \frac{\theta_4}{2\pi}
\end{align*}
\]

where \( \theta_1, \theta_2, \theta_3, \text{and} \theta_4 \) are the probabilities that the nodes corresponding to \( q_1 \) and \( q_2 \) are aligned in a direction that provides antenna gains \( G_{q_1}^{(\text{max})} \) and \( G_{q_2}^{(\text{max})} \), respectively.

4) Association Rule and Interference:

a) Association Rule: Let \( P_{R} \) be the total transmit power budget for serving MTs. Let \( P_{R_q}^{(C)(1)} \), \( P_{R_q}^{(W)(1)} \), and \( P_{R_q}^{(C)(2)} \) denote the transmit powers of \( R_q^{(C)}(1) \), \( R_q^{(W)}(1) \), and \( R_q^{(C)}(2) \), respectively. In order to ensure the total power constraint [41] as our design aim, they are defined by \( P_{R_q}^{(C)(1)} = \)

3Antenna arrays with important gains that are suitable for the size of MTs and are, for instance, based on both dipoles and patch antennas have been proposed in the literature [39], [40].

4We assume that the wireless RRHs are equipped with separate receive and transmit RF chains and antennas.

5It is out of the scope of this work the consideration of imperfect channel knowledge at the serving RRHs that can lead to beam misalignment errors.
$P_R$, $P_{R_o}^{(w)} = (1 - K_R)P_R$, and $P_{R_o}^{(c)(2)} = K_RP_R$, where $0 < K_R < 1$ is a power-splitting coefficient.

Similar to [8], the triplet $R_o^{(c)(1)}, R_o^{(w)}$, and $R_o^{(c)(2)}$ is identified by using the following criteria:

$$R_o^{(c)(1)} = \arg \min_{R_i^{(c)} \in \Phi_i^{(c)}} \left\{ \frac{l_s(R_i^{(c)}, MT)}{P_R G_{R_i^{(c)}}^{(max)} G_{MT}^{(max)}} \right\} \tag{4}$$

$$R_o^{(W)} = \arg \min_{R_i^{(W)} \in \Phi_i^{(W)}} \left\{ \frac{l_s(R_i^{(W)}, MT)}{(1 - K_R)P_R G_{R_i^{(W)}}^{(max)} G_{MT}^{(max)}} \right\} \tag{5}$$

$$R_o^{(c)(2)} = \arg \min_{R_i^{(c)} \in \Phi_i^{(c)}} \left\{ \frac{l_s(R_i^{(c)}, R_i^{(W)})}{K_R P_R G_{R_i^{(c)}}^{(max)} G_{R_i^{(W)}}^{(max)}} \right\} \tag{6}$$

where $s_i, s_e, s_j \in \{LOS, NLOS\}$ and $R_{X,Y}$ denotes the distance between the nodes $X$ and $Y$. The association criteria in (4), (5), and (6) ensure that $MT_0$ receives the highest power from the available fiber-connected and wireless RRHs as well as that the serving wireless RRH, $R_o^{(w)}$, receives the highest power from the available RRHs.

Let the triplet of network elements $R_o^{(c)(1)}$, $R_o^{(w)}$, and $R_o^{(c)(2)}$ from (4), (5), and (6), respectively. The typical MT, $MT_o$, is served either via a one- or a two-hop link according to the cell-association criterion as follows [8]:

$$\begin{cases} 1 \text{ hop, if } & B_{BS} P_R G_{R_o^{(c)(1)}}^{(max)} G_{MT}^{(max)} \\ \leq & \frac{l_s(R_o^{(c)(1)}, MT_o)}{P_R G_{R_o^{(c)(1)}}^{(max)} G_{MT}^{(max)}} \tag{7} \\
2 \text{ hops, otherwise,} & \\
\end{cases}$$

where $B_{BS}$ is a non-negative constant, which is called bias coefficient. Depending on its value, it prioritizes either the single-hop or the two-hop transmission conditioned on the values of the path-loss exponents. In particular, the communication takes place in one hop if $B_{BS} = \infty$ and in two hops if $B_{BS} = 0$.

b) Interfering Processes: The set of interfering fiber-connected and wireless RRHs are denoted by $\Phi_i^{(f)}$ and $\Phi_i^{(W)}$, respectively. In addition, $\Phi_i^{(f)}$ can be split into two disjoint sets, $\Phi_i^{(1,1\text{hop})}$ and $\Phi_i^{(2,1\text{hop})}$, corresponding to the interfering fiber-connected RRHs serving their associated MTs either via a one- and two-hop link, respectively. Since the cell-association rules (4)-(7) are distance-dependent, the sets $\Phi_i^{(1,1\text{hop})}$ and $\Phi_i^{(2,1\text{hop})}$ are not homogeneous PPPs.

In addition, the number of the interfering wireless RRHs is equal to the number of the interfering fiber-connected RRHs participating in the two-hop transmissions since both convey signals using the whole available bandwidth, according to the TDMA protocol. As with $\Phi_i^{(1,1\text{hop})}$ and $\Phi_i^{(2,1\text{hop})}$, $\Phi_i^{(W)}$ is not a homogeneous PPP due to the association protocol of (4)-(7).

5) Operational Principle of the Wireless RRHs: We consider two types of wireless RRHs: i) HD; ii) FD. In the following, we describe their operational principle:

a) HD RRHs: According to the HD principle, the wireless RRHs receive and transmit in different time slots. The end-to-end communication is realized in two phases that have a duration of one time slot each and are described as follows:

1st Phase: During the 1st phase, the fiber-connected RRHs convey their signals towards their respective wireless RRHs and MTs.

2nd Phase: During the 2nd phase, the transmissions that are allowed are the ones of the fiber-connected and wireless RRHs towards the MTs that they serve.

Hence, if an MT is served by a wireless RRH the symbol rate is equal to 0.5 symbols/time slot.

b) FD RRHs: According to the FD principle, the wireless RRHs receive and transmit in the same time slot. As in the HD case, the end-to-end communication is realized in two phases that have a duration of one time slot each and are described as follows:

1st Phase: During the 1st phase, the fiber-connected RRHs convey their signals towards their respective wireless RRHs and MTs. More specifically, assuming that $MT_o$ is served through $R_o^{(c)}$, in time slot $n$ $R_o^{(c)(2)}$ conveys the symbol $s_n$ while in the same time slot $R_o^{(W)}$ conveys to $MT_o$ the symbol $s_n'$, which is the detected symbol that corresponds to the symbol conveyed from $R_o^{(c)(2)}$ to $R_o^{(W)}$ in time slot $n - 1$. Hence, the received signal of $R_o^{(W)}$ in time slot $n$ is subject to self interference due to its concurrent transmission.

2nd Phase: During the 2nd phase, both fiber-connected and wireless RRHs are allowed to transmit, as in the 1st phase. More specifically, in time slot $n + 1$ $R_o^{(c)(2)}$ conveys to $R_o^{(W)}$ the symbol $s_{n+1}$ while in the same time slot $R_o^{(W)}$ conveys to $MT_o$ the symbol $s_n'$, which is the detected symbol that corresponds to the symbol conveyed from $R_o^{(c)(2)}$ to $R_o^{(W)}$ in time slot $n$. Hence, the received signal at $MT_o$ in time slot $n + 1$ is subject to interference originating from $R_o^{(c)(2)}$ due to the concurrent transmission of $s_{n+1}$. Due to the concurrent reception and transmission of $R_o^{(W)}$, as $n \to \infty$ the symbol rate of the FD operation asymptotically tends to 1 symbol/time slot, which is the same as the one of the one-hop case.

6) Characteristics of the Self-Interference Signal in the FD Case: Such a signal consists of two components [42]: i) A LOS component originating from the direct signal reaching the receive antenna of $R_o^{(W)}$ due to the concurrent transmission; ii) A NLOS component due to the reflections from obstacles in the radio path of the conveyed signal of $R_o^{(W)}$ that reach its receive antenna. In sub-6 GHz bands, measurements have shown that the power level of the LOS component is in general much higher than the corresponding one of the NLOS component [42]. This necessitates the sophisticated design of FD nodes through analog and digital self-interference cancellation techniques so that the power level of the self-interfering signal falls below the noise floor. This poses substantial challenges regarding the design of sub-6 GHz FD nodes.

On the other hand, for mmWave bands theoretical and experimental works have shown that in the 28-GHz band it is highly probable that the NLOS component is stronger than the
LOS component [43], [44]. According to these works, around 70-80 dB of self-interference mitigation can be achieved through antenna directionality and 35-50 dB of mitigation can be achieved through analog and digital techniques.

As far as the modeling of the self-interfering signal is concerned, the sub-6 GHz band related literature works mainly model it as a Rayleigh or a Rice random variable with variance that represents its residual power level after the cancellation stages [42]. To the best of our knowledge, in mmWave bands there is a lack of experimental studies regarding the statistical characteristics of such a signal. Due to this and taking into account that in this work we are primarily interested in examining the effect of the mean power level of the self-interfering signal, in this work we model it as a fixed variable, denoted by $\sigma^2_{fi}$.

Notation: Recurrent parameters are included in Table II.

III. INSTANTANEOUS SINR EXPRESSIONS AND EXAMINED METRIC

In this section, we first present the signal model, subsequently we introduce the instantaneous SINR expressions for each of the HD and FD cases and, finally, we mathematically formulate the coverage rate as the metric of interest.

A. Signal Model

1) HD Case:

a) One-Hop Communication: In such a case, the received signal at $MT_0$, denoted by $y_{R_0^C(1),MT_0}$, is given by

$$y_{R_0^C(1),MT_0} = \sqrt{P_R G^{(\text{max})}_{R,C} G_{MT}^{(\text{max})}} \left( R_0^{(1),MT_0} \right)^{-\frac{1}{2}}$$

$$\times h_{R_0^C(1),MT_0} s_o + n_{MT_0}^{(1)} + i_{R,C(1),MT_0} + i_{R,MT_0},$$

where $s_o$ is the transmitted symbol in time slot $n$, $n_{MT_0}$ is the noise at $MT_0$, $i_{R,C(1),MT_0}$ is the interference process resulting from the set of fiber-connected RRHs constituting the single-hop transmissions and $i_{R,MT_0} \in \{i_{R,C(1),MT_0}, i_{R,WMT_0} \}$. $i_{R,C(2),MT_0}$ and $i_{R,WMT_0}$ are the interference processes resulting from the set of fiber-connected RRHs constituting the two-hop transmissions and the set of wireless RRHs, respectively. It holds that

$$i_{R,C(1),MT_0} = \sum_{R_0^C(1) \in \Phi_{R,C(1)}^{(1,2,\text{hop})}} \sqrt{P_R G^{(m_{11})}_{R,C} G_{MT}^{(m_{21})}} h_{R_0^C(1),MT_0} s_i$$

$$\times \left[ \sum_{s_i} \left( R^{(1),MT_0} \right)^{-\frac{1}{2}} \left( R_{R_0^C(1),MT_0}^{(1)} \right)^{-\frac{1}{2}} \right]^{-\frac{1}{2}}$$

$$1 \left( R^{(1),MT_0} \right)^{-\frac{1}{2}} \left( R_{R_0^C(1),MT_0}^{(1)} \right)^{-\frac{1}{2}}$$

$$> l_{s_i} \left( R^{(1),MT_0} \right)^{-\frac{1}{2}} \left( R_{R_0^C(1),MT_0}^{(1)} \right)^{-\frac{1}{2}}.$$

Notation: Recurrent parameters are included in Table II.

$$\begin{array}{|c|c|}
\hline
\text{Symbol} & \text{Meaning} \\
\hline
\Phi_{R,C(1)}^{(1)} & \text{PPP of fiber-connected RRHs} \\
\Phi_{R,WMT}^{(1)} & \text{PPP of wireless RRHs} \\
\Phi_{MT}^{(1)} & \text{PPP of MTs} \\
\Phi_{R,C(2)}^{(1)} & \text{PPP of interfering fiber-connected RRHs} \\
\Phi_{R,WMT}^{(1)} & \text{PPP of interfering wireless RRHs} \\
\Phi_{R,C(2)}^{(1,2,\text{hop})} & \text{PPP of interfering fiber-connected RRHs serving their MTs via one hop} \\
\Phi_{R,WMT}^{(1,2,\text{hop})} & \text{PPP of interfering fiber-connected RRHs serving their MTs via two hops} \\
\frac{\lambda_{R_C}, \lambda_G}{\lambda_{MT}, \lambda_{BBU}} & \text{Densities of fiber-connected RRHs, wireless RRHs, MTs, and BBUs, respectively} \\
\frac{R_0^{(1)}, R_0^{(2)}}{R_0^{(1)}, R_0^{(2)}} & \text{One- and two-hop serving fiber-connected RRHs, respectively} \\
\frac{R_0^{(W)}}{MT_0} & \text{Reference MT} \\
\hline
\end{array}$$

TABLE II

where $s_i, s_k, s_o \in \{\text{LOS, NLOS}\}$ and $m_{11}, m_{1k}, m_{21}, m_{2k} \in \{\text{min, max}\}$.

b) Two-Hop Communication: For the communication between $R_0^{(1)}$ and $R_0^{(2)}$, the received signal at $R_0^{(1)}$,
we denote by $y^{(HD)}_{R_o^{(C)(2)}, R_o^{(W)}}$, is given by
\[ y^{(HD)}_{R_o^{(C)(2)}, R_o^{(W)}} = \sqrt{K_R P_R G_{R_o^{(C)}}(max) G_{R_o^{(W)}} G_{MT}} s_{o_n} \]
\[ \times \sqrt{\left[ l_{s_n} \left( \frac{R_o^{(C)(2)}, R_o^{(W)}}{l_{s_n}} \right) \left( R_o^{(C)(2)}, R_o^{(W)} \right)^{-1} \right]} + n_{R_o^{(W)}} + i_{R_o^{(C)(1)}, R_o^{(W)}} + i_{R_o^{(C)(2)}, R_o^{(W)}} , \]
\[ (12) \]
where $n_{R_o^{(W)}}$ is the noise at $R_o^{(W)}$ and $i_{R_o^{(C)(1)}, R_o^{(W)}}$ and
\[ i_{R_o^{(C)(2)}, R_o^{(W)}} \]
are the interference processes resulting from the set of fiber-connected RRHs constituting the one- and two-hop transmissions, respectively. It holds that
\[ i_{R_o^{(C)(1)}, R_o^{(W)}} = \sum_{R_o^{(C)(1)} \in \Phi} \sqrt{K_R P_R G_{R_o^{(C)}}(max) G_{R_o^{(W)}}} s_{s_n} \]
\[ \times \sqrt{\left[ l_{s_n} \left( \frac{R_o^{(C)(1)}, R_o^{(W)}}{l_{s_n}} \right) \left( R_o^{(C)(1)}, R_o^{(W)} \right)^{-1} \right]} + 1 \left( l_{s_n} \left( \frac{R_o^{(C)}, R_o^{(W)}}{l_{s_n}} \right) \right) \left( R_o^{(C)(1)}, R_o^{(W)} \right) , \]
\[ (13) \]
\[ i_{R_o^{(C)(2)}, R_o^{(W)}} = \sum_{R_o^{(C)(2)} \in \Phi} \sqrt{K_R P_R G_{R_o^{(C)}}(max) G_{R_o^{(W)}}} s_{s_n} \]
\[ \times \sqrt{\left[ l_{s_n} \left( \frac{R_o^{(C)(2)}, R_o^{(W)}}{l_{s_n}} \right) \left( R_o^{(C)(2)}, R_o^{(W)} \right)^{-1} \right]} + 1 \left( l_{s_n} \left( \frac{R_o^{(C)}, R_o^{(W)}}{l_{s_n}} \right) \right) \left( R_o^{(C)(2)}, R_o^{(W)} \right) , \]
\[ (14) \]
As far as the communication between $R_o^{(W)}$ and $MT_o$ in the 2nd phase is concerned, the received signal at $MT_o$, which we denote by $y^{(HD)}_{R_o^{(W)}, MT_o}$ is given by
\[ y^{(HD)}_{R_o^{(W)}, MT_o} = \sqrt{\left( 1 - K_R \right) P_R G_{R_o^{(W)}}(max) G_{MT}} s_{o_n} \]
\[ \times \sqrt{\left[ l_{s_n} \left( \frac{R_o^{(W)}, MT_o}{l_{s_n}} \right) \left( R_o^{(W)}, MT_o \right)^{-1} \right]} + n_{MT_o} + i_{R_o^{(C)(1)}, MT_o} + i_{R_o^{(C)(2)}, MT_o} , \]
\[ (15) \]
where $s_{o_n}$ is the decoded and remodulated transmitted symbol at $R_o^{(W)}$, $n_{MT_o}$ is the noise at $MT_o$ and $i_{R_o^{(C)(1)}, MT_o}$ and $i_{R_o^{(C)(2)}, MT_o}$ are the interference processes resulting from the set of fiber-connected RRHs constituting the one-hop transmissions and the set of wireless RRHs, respectively. It holds that
\[ i_{R_o^{(C)(1)}, MT_o}^{(2)} \]
\[ i_{R_o^{(C)(2)}, MT_o}^{(2)} \]
\[ (16) \]
where $s_i, s_k, s_o \in \{ LOS, NLOS \}$ and $m_1, m_1, m_2, m_2 \in \{ min, max \}$, where $s_k$ are the decoded and remodulated transmitted symbols from the respective interfering wireless RRHs.

2) FD Case:

a) One-Hop Communication: In the case of one-hop communication, the received signal at $MT_o$, which is denoted by $y^{(FD)}_{R_o^{(C)(1)}, MT_o}$, is given by
\[ y^{(FD)}_{R_o^{(C)(1)}, MT_o} = \sqrt{P_R G_{R_o^{(C)}}(max) G_{MT}} \left[ l_{s_n} \left( \frac{R_o^{(C)}, MT_o}{l_{s_n}} \right) \left( R_o^{(C)}, MT_o \right)^{-1} \right) \]
\[ \times h_{R_o^{(C)(1)}, MT_o} s_{o_n} + n_{MT_o} + i_{R_o^{(C)(1)}, MT_o}^{(2)} \]
\[ + i_{R_o^{(C)(2)}, MT_o}^{(2)} , \]
\[ (17) \]
where the interference processes $i_{R_o^{(C)(1)}, MT_o}$ and $i_{R_o^{(C)(2)}, MT_o}$ are defined in (9), (10), and (11), respectively.

b) Two-Hop Communication: For the communication between $R_o^{(C)(2)}$ and $R_o^{(W)}$, the received signal at $R_o^{(W)}$, which we denote by $y^{(FD)}_{R_o^{(C)(2)}, R_o^{(W)}}$, is given by
\[ y^{(FD)}_{R_o^{(C)(2)}, R_o^{(W)}} = \sqrt{K_R P_R G_{R_o^{(C)}}(max) G_{R_o^{(W)}}} s_{o_n} \]
\[ \times \sqrt{\left[ l_{s_n} \left( \frac{R_o^{(C)(2)}, R_o^{(W)}}{l_{s_n}} \right) \left( R_o^{(C)(2)}, R_o^{(W)} \right)^{-1} \right]} + n_{R_o^{(W)}} \]
\[ + i_{R_o^{(C)(1)}, R_o^{(W)}} s_{o_n} + i_{R_o^{(C)(2)}, R_o^{(W)}} \]
\[ + i_{R_o^{(W)}, R_o^{(W)}} , \]
\[ (18) \]
where $i_{R_o^{(C)(1)}, R_o^{(W)}}$ and $i_{R_o^{(C)(2)}, R_o^{(W)}}$ are defined in (13) and (14), respectively, and $i_{R_o^{(W)}, R_o^{(W)}}$ is the interference process.
process originating from the interfering RRHs that concurrently transmit. It holds that

\[ i_{R^{(w)}, s_{n}}^{(w)} = \sum_{R_{k}^{(w)} \in \Phi_{R_{k}^{(w)}}} \sqrt{(1 - K_{R}) \, P_{R} G_{R^{(w)}} \left( \frac{m_{1}}{R_{k}^{(w)}}, R_{k}^{(w)} \right) G_{s}^{(w)} s_{k}^{(w)}} \]

\[ \times \left[ \left( i_{s_{k}}^{(w), MT} \left( R_{k}^{(w)}, R_{o}^{(w)} \right) \right)^{-1} + h_{R_{k}^{(w)}, MT_{o}}^{(2)} \right] \]

\[ \times \left[ \left( i_{s_{k}}^{(w), MT} \left( R_{k}^{(w)}, MT_{o} \right) \right)^{-1} + h_{R_{k}^{(w)}, MT_{o}}^{(2)} \right] \]

\[ > i_{s_{k}}^{(w), MT} \left( R_{k}^{(w)}, MT_{o} \right) \] \quad \text{(20)}

As far as the communication between \( R_{o}^{(w)} \) and \( MT_{o} \) in the 2nd phase is concerned, the received signal at \( MT_{o} \), which we denote by \( y_{R^{(w)}, MT_{o}}^{(FD)} \), is given by

\[ y_{R^{(w)}, MT_{o}}^{(FD)} = \sum_{R_{k}^{(w)} \in \Phi_{R_{k}^{(w)}}} \sqrt{(1 - K_{R}) \, P_{R} G_{R^{(w)}} \left( \frac{m_{1}}{R_{k}^{(w)}}, R_{k}^{(w)} \right) G_{s}^{(w)} s_{k}^{(w)}} \]

\[ \times \left[ \left( i_{s_{k}}^{(w), MT} \left( R_{k}^{(w)}, MT_{o} \right) \right)^{-1} + h_{R_{k}^{(w)}, MT_{o}}^{(2)} \right] \]

\[ + i_{R^{(C)}}^{(2), MT_{o}} + i_{R^{(C)}}^{(2), MT_{o}} + i_{R^{(C)}}^{(2), MT_{o}} \] \quad \text{(21)}

where \( i_{R^{(C)}}^{(2), MT_{o}} \) is the interfering signal reaching \( MT_{o} \) due to the transmission from \( R_{o}^{(C)} \) in the time slot \( n + 1 \) of the symbol \( s_{o,n+1} \) that is intended to \( R_{o}^{(w)} \) and \( i_{R^{(C)}}^{(2), MT_{o}} \) is the interference process resulting from the set of interfering fiber-connected RRHs that serve their MTs through a two-hop transmission. In addition, \( i_{R^{(C)}}^{(2), MT_{o}} \) and \( i_{R^{(C)}}^{(2), MT_{o}} \) are defined in (16) and (17), respectively. Regarding \( i_{R^{(C)}}^{(2), MT_{o}} \) and \( i_{R^{(C)}}^{(2), MT_{o}} \) they are given by

\[ i_{R^{(C)}}^{(2), MT_{o}} = \sqrt{K_{P} \, P_{R} G_{R^{(C)}} \left( \frac{m_{1}}{R_{o}^{(C)}}, MT_{o} \right) G_{s}^{(MT)} s_{o,n+1} \right] \]

\[ \times \left[ \left( i_{s_{k}}^{(C), MT} \left( R_{o}^{(C)}, MT_{o} \right) \right)^{-1} + h_{R_{o}^{(C)}, MT_{o}}^{(2)} \right] \]

\[ \times \left[ \left( i_{s_{k}}^{(C), MT} \left( R_{o}^{(C)}, MT_{o} \right) \right)^{-1} + h_{R_{o}^{(C)}, MT_{o}}^{(2)} \right] \]

\[ > i_{s_{k}}^{(C), MT} \left( R_{o}^{(C)}, MT_{o} \right) \] \quad \text{(22)}

\[ \text{B. Instantaneous SINR} \]

1) HD Case:

a) One-Hop Communication: In the case of one-hop communication, the instantaneous SINR at \( MT_{o} \), which is denoted by \( SINR_{R_{o}^{(C)}, MT_{o}}^{(HD)} \), is given by

\[ SINR_{R_{o}^{(C)}, MT_{o}}^{(HD)} = P_{R} \left[ h_{R_{o}^{(C)}, MT_{o}}^{(max)} G_{R^{(C)}} G_{s}^{(max)} \right] \]

\[ \times \left[ \left( i_{s_{k}}^{(C), MT} \left( R_{o}^{(C)}, MT_{o} \right) \right)^{-1} + h_{R_{o}^{(C)}, MT_{o}}^{(2)} \right] \]

\[ > i_{s_{k}}^{(C), MT} \left( R_{o}^{(C)}, MT_{o} \right) \] \quad \text{(23)}

6For instance, a linear array of 50 dipole antennas with half-wavelength distance between adjacent dipoles occupies a length of around 27 cm in the 28 GHz band. On the other hand, for the 2.1 GHz band such an array occupies a length of around 3.6 m. Such a size is not suitable for compact RRH nodes that are, for instance, mounted on lampposts.
Communication, the instantaneous SINR at MT between 7770 IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 68, NO. 12, DECEMBER 2020

\[ R_{C}(C) \]

is denoted by

\[ R_{C}(C) \]

For the communication between \( R_{0}(W) \) and \( M_{T} \), the received SINR at \( R_{0}(W) \), which we denote by \( SINR_{R_{0}(W)} \), is given by

\[
SINR_{R_{0}(W)}^{(HD)} = K_{R} P_{R} R_{C}(C) G_{R_{0}(W)}^{(max)} \times \left[ I_{s_{o}} \left( R_{C}(C), R_{0}(W) \right) \right]^{-1}
\]

\[
\times \left( \sigma_N^2 + I_{R_{C}(C)}(1), R_{0}(W) + I_{R_{C}(C)}(2), R_{0}(W) \right)^{-1},
\]

where \( I_{R_{C}(C)}(1), R_{0}(W) \) and \( I_{R_{C}(C)}(2), R_{0}(W) \) are the variances of \( i_{R_{C}(C)}(1), R_{0}(W) \) and \( i_{R_{C}(C)}(2), R_{0}(W) \), respectively.

As far as the communication between \( R_{0}(W) \) and \( M_{T} \) in the 2nd phase is concerned, the received SINR at \( M_{T} \), which we denote by \( SINR_{M_{T}}^{(FD)} \), is given by

\[
SINR_{M_{T}}^{(FD)} = K_{R} P_{R} R_{C}(C) G_{M_{T}}^{(max)} \times \left[ I_{s_{o}} \left( R_{C}(C), M_{T} \right) \right]^{-1}
\]

\[
\times \left( \sigma_N^2 + I_{R_{C}(C)}(1), M_{T} + I_{R_{C}(C)}(2), M_{T} \right)^{-1},
\]

where \( I_{R_{C}(C)}(1), M_{T} \) and \( I_{R_{C}(C)}(2), M_{T} \) are the variances of \( i_{R_{C}(C)}(1), M_{T} \) and \( i_{R_{C}(C)}(2), M_{T} \), respectively.

C. Coverage-Rate Formulation

The coverage rate, which is denoted by \( R_{cov}^{(HD)} \) \((R_{t})\) and \( R_{cov}^{(FD)} \) \((R_{t})\) in the HD and FD cases, respectively, is defined as the probability that the instantaneous rate is larger than a threshold \( R_{t} \). It is given by the sum of the following terms: i) The coverage rate in the case of 1-hop communication, which is equal to the average value with respect to \( R_{R_{C}(C)}(1), M_{T} \) of the product of the probability that the communication is realized in 1 hop and the probability that the instantaneous rate is larger than \( R_{t} \), where both probabilities are conditioned on \( R_{R_{C}(C)}(1), M_{T} \); ii) The coverage rate in the case of 2-hop communication, which is equal to the average value with respect to \( R_{R_{C}(C)}(2), M_{T} \) of the product of the probability that the communication is realized in 2 hops and the probability that the instantaneous rate is larger than \( R_{t} \), where both probabilities are conditioned on \( R_{R_{C}(C)}(2), M_{T} \). Mathematically, it is formulated as

\[
R_{cov}^{(HD)} = E_{R_{R_{C}(C)}(1), M_{T}} \left\{ R_{cov}^{(1, hop)} \left( R_{t}; R_{R_{C}(C)}(1), M_{T} \right) \right\}
\]

\[
+ E_{R_{R_{C}(C)}(2), M_{T}} \left\{ R_{cov}^{(2, hop)} \left( R_{t}; R_{R_{C}(C)}(2), M_{T} \right) \right\},
\]

where \( l \in \{ HD, FD \} \) and

\[
R_{cov}^{(1, hop)} \left( R_{t}; R_{u} \right) = \Pr \left\{ \frac{BW}{N_{MT}} \log_2 \left( 1 + SINR_{u}^{(l)} \right) > R_{t} \bigg| R_{u} \right\}
\]

\[
\times \Pr \left\{ I_{s_{o}} \left( R_{C}(C), R_{u} \right) \right\}
\]

\[
\times \left( \sigma_N^2 + \sigma_S^2 I + I_{R_{C}(C)}(1), R_{u} + I_{R_{C}(C)}(2), R_{u} \right)^{-1},
\]

\[
\frac{1}{B_{BS} G_{R_{C}(C)}^{(max)}} \left( I_{s_{o}} \left( R_{C}(C), M_{T} \right) \right) (R_{u}) \bigg| R_{u} \right\},
\]

\[
R_{cov}^{(2, hop)} \left( R_{t}; R_{u} \right) = \Pr \left\{ F^{(l)} \left( SINR_{u}^{(l)} \right) > R_{t} \bigg| R_{u} \right\}
\]

\[
\times \Pr \left\{ I_{s_{o}} \left( R_{C}(C), M_{T} \right) \right\}
\]

\[
\times \left( \sigma_N^2 + \sigma_S^2 I + I_{R_{C}(C)}(1), M_{T} + I_{R_{C}(C)}(2), M_{T} \right)^{-1},
\]

where \( I_{R_{C}(C)}(1), M_{T} \) and \( I_{R_{C}(C)}(2), M_{T} \) are the variances of \( i_{R_{C}(C)}(1), M_{T} \) and \( i_{R_{C}(C)}(2), M_{T} \), respectively.
we denote by $H$. Hence, the resulting approximate SINR expressions, which limited approximation regarding the intercell interference.

IV. PERFORMANCE ANALYSIS AND INSIGHTS

The aim of this section is: i) To present an analytical approximate expression of the coverage rate for each of the HD and FD cases; ii) To extract important trends regarding the performance comparison of these two cases for different regions regarding the ratio of the density of the wireless RRHs over the one of the fiber-connected ones; iii) To present an analytical expression of the coverage rate.

Towards these, we first present the considered noise-limited and LOS ball approximations that enable us to derive an analytical expression of the coverage rate.

A. Noise-Limited Approximation

As we have mentioned in Remark 1, it is expected that the the considered network is noise limited even for dense RRH topologies. This is due to the considered TDMA protocol and the resulting large bandwidth per transmission, the high directionality that is possible in the considered band of 28 GHz, and the high density in blockages that exists in urban scenarios. Due to this, for the extraction of an analytical expression for $R(l)_{cov}$ ($R_t$), $l \in \{HD,FD\}$ we consider the noise-limited approximation regarding the intercell interference. Hence, the resulting approximate SINR expressions, which we denote by $SINR(l)_{R(l)}^{(NL)}$ and $SINR(l)_{R(l)}^{(NL),MT}$, are given by

$$
SINR(l)_{R(l)}^{(NL),MT} = \left. \frac{E_{BST}G^{(max)} \left( R(l)_{cov}^{(W)}(u) \right) (R_u) | R_u \right] \right) \right(1 - K_R) G^{(max)} \left( R(l)_{cov}^{(W)}(u) \right) (R_u) | R_u \right],
$$

with

$$
F(l) \left( \text{SINR}_u(l) \right) = \frac{\xi (l) \text{BW}}{N_{MT}} \log_2 \left( 1 + \min \left\{ \text{SINR}_u(l)_{R(l)}^{(NL), MT}, \text{SINR}_u(l)_{R(l)}^{(NL), MT} \right\} \right).
$$

$N_{MT}$ is the number of MTs served (either directly or through wireless RRHs) by the fiber-connected RRH that is associated with the reference MT and $\xi(HD) = \frac{1}{2}, \xi(FD) = 1$.

B. LOS Ball Approximation

Due to the complicated forms of the probability density function of a MT or RRH to its nearest LOS or NLOS RRH [17, Eq. (6)], [17, Eq. (7)], we consider the LOS approximation that is commonly used in analyzing mmWave cellular networks [17], [36]. According to it, up to a certain distance the probability that the link is LOS is 1 and 0 above it. Hence, we distinguish 3 breaking distances for the

C. Performance Analysis

Before proceeding with the analytical expression of $R(l)_{cov}$, $l \in \{HD,FD\}$, we first present Lemma 1.

**Lemma 1:** The probability that $N_{MT}$ is equal to $n$, where $n = 1, 2, 3, \ldots$, which is denoted by $P_r \{ N_{MT} = n \}$, is given by

$$
P_r \{ N_{MT} = n \} = \frac{3.5^{3.5} \Gamma(n + 3.5) (\lambda_{MT}/\lambda_{MT}^{(C)})^{n-1}}{(n-1)! \Gamma(3.5)} (3.5 + \lambda_{MT}/\lambda_{MT}^{(C)})^{-n-3.5}.
$$

**Proof:** (37) originates from the typical Poisson-Voronoi tessellation [36, Section III-C]. Although the distribution of the association areas of the fiber-connected RRHs would be different due to the LOS and NLOS conditions originating from blockages together with the presence of wireless RRHs, the mean area that they cover is the same as the mean area of the typical Poisson-Voronoi tessellation [36, Section III-C].

**Proposition 1:** $R(l)_{cov}(R_t)$, where $l \in \{HD,FD\}$, can be approximated as

$$
R(l)_{cov}(R_t) \approx R(l)_{cov}^{(1,hop)}(R_t) + R(l)_{cov}^{(2,hop)}(R_t) = \left. \sum_{n=1}^{N_{transc}} \Pr \{ N_{MT} = n \} \sum_{s_{1,a},s_{2,a} \in \{LOS,NLOS\}} R(l)_{cov}^{(v_{1,a},s_{1,a},s_{2,a})}(n,R_t),
$$

where

$$
R(l)_{cov}^{(1,hop)}(R_t) = \sum_{n=1}^{N_{transc}} \Pr \{ N_{MT} = n \} \sum_{s_{1,a} \in \{LOS,NLOS\}} R(l)_{cov}^{(v_{1,a},s_{1,a})}(n,R_t),
$$

and

$$
R(l)_{cov}^{(2,hop)}(R_t) = \left. \sum_{n=1}^{N_{transc}} \Pr \{ N_{MT} = n \} \sum_{s_{1,a},s_{2,a} \in \{LOS,NLOS\}} R(l)_{cov}^{(v_{1,a},s_{1,a},s_{2,a})}(n,R_t).
$$

A necessary and sufficient condition for (38) is that

$$
\int_{0}^{\infty} \prod_{i=1}^{4} R(l)_{cov}^{(v_{1,a},s_{1,a})}(n,R_t) \Theta_{s_{1,a},s_{2,a}}(x) dx
$$
\[ f^{(\psi)}_1(x) = x^{+\psi}NLOS \times \exp\left[-c_{\psi} x^{+\psi} \left(2\frac{m_R}{2\pi} - 1\right)\right] dx, \] 
\[ R^{(\psi_2)}_N(n, R_t) = \int_0^{m_{R_2}} \prod_{k=1}^4 f^{(\psi_2)}_k(x) \Theta_{\psi_{1_0}, \psi_{2_0}}(x) dx, \] 
\[ \Theta_{\psi_{1_0}, \psi_{2_0}}(x) = \int_{-\infty}^{+\infty} \prod_{k=1}^4 f^{(\psi_2)}_k(y) dy, \]
\[ \Theta_{\psi_{1_0}, \psi_{2_0}}(x) = \int_{-\infty}^{+\infty} \prod_{k=1}^4 f^{(\psi_2)}_k(y) dy, \]

where \( \zeta(HD) = \frac{1}{2} \) and \( \zeta(FD) = 1 \).

\[ f^{(\psi)}_1(x) = x^{+\psi}NLOS, \quad f^{(\psi)}_2(x) = 2\pi\lambda x \exp(-\beta x), \] 
\[ f^{(\psi)}_3(x) = \exp\left(-2\pi\lambda_x(1 - \exp(-\beta x)) (\beta x + 1)\right), \] 
\[ f^{(\psi)}_4(x) = \exp\left[-2\pi\lambda_x \left(\frac{f^{(\psi)}_2(x)^2}{2} - \frac{1}{\beta^2}\right)\right] \times \exp\left[-2\pi\lambda_x (\beta f^{(\psi)}_1(x) + 1) \exp(-\beta f^{(\psi)}_1(x))\right], \] 
\[ f^{(\psi)}_1(x) = x^{+\psi}NLOS, \quad f^{(\psi)}_2(x) = 2\pi\lambda x \left(1 - \exp(-\beta x)\right), \] 
\[ f^{(\psi)}_3(x) = \exp\left(-2\pi\lambda_x \left(\frac{x^2}{2} - \frac{1 - (\beta x + 1) \exp(-\beta x)}{\beta^2}\right)\right), \] 
\[ f^{(\psi)}_4(x) = \exp\left(-2\pi\lambda_x \left(1 - \exp(-p^{(\psi)}(x))\right) \left(p^{(\psi)}(x) + 1\right)\right), \]

where \( \psi \in \{\psi_{1_0}, \psi_{2_0}, \psi_{3_0}\} \) and \( p^{(\psi)}(x) = \beta f^{(\psi)}_1(x) \).

It holds that
\[ f^{(\psi)}_1(x) = \begin{cases} \frac{R^{(\psi)}_N(x)}{R^{(\psi)}_N(x) + x NLOS}, & \text{for } \psi = \{\psi_{1_0}, \psi_{2_0}, \psi_{3_0}\}, \text{ respectively.} \\
(1 - K_R) G^{(max)}_{R'(WC)}(x), & \text{for } \psi = \{\lambda_R^{(C)}, \lambda_R^{(W)}, \lambda_R^{(C)}\}, \text{ respectively.} \end{cases} \]

for \( \psi = \{\psi_{1_0}, \psi_{2_0}, \psi_{3_0}\} \), respectively. In addition, \( \lambda_\psi = \{\lambda_R^{(C)}, \lambda_R^{(W)}, \lambda_R^{(C)}\} \) and

\[ \kappa_a \sigma^2_N \frac{C_{\psi_{3_0}}(n, R_t)}{G^{(max)}_{R'N} G^{(max)}_{R'T外}} \cdot \left(1 - K_R\right) G^{(max)}_{R'NC} G^{(max)}_{R'T外} \]

where \( \zeta(HD) = 0 \) and \( \zeta(FD) = \sigma^2_S \). \( R^{(\text{hop})}_{N\text{trunc}}(R_t) \) and \( R^{(\text{hop})}_{N\text{trunc}}(R_t) \) are the coverage rates in the case that the communication is realized in 1 or 2 hops, respectively. They are given by the probability of having 1- or 2-hop communication multiplied by the probability that the instantaneous rate in each case is larger than a threshold \( R_t \), taking into account all the possible combinations of the involved links \( R^{(\text{CF})}, R^{(\text{CF})} \) and \( R^{(\text{CF})}, R^{(\text{CF})} \) being LOS or NLOS, which leads to (41)-(53). In addition, \( N_{\text{trunc}} \) is introduced so that the series in (39) and (40) are not infinite. A rule of thumb for the choice of \( N_{\text{trunc}} \) is that it should be a multiple of \( \frac{K_{\text{MT}}}{\lambda_{R^{(C)}}} \) [36].

**Proof:** See APPENDIX A.

Remark 2: The computational complexity of (38) can be substantially reduced at the cost of accuracy by removing the summation over the possible number of MTs per fiber-connected cell and replacing \( n \) in \( R^{(\text{hop})}_{N\text{trunc}}(R_t) \) and \( R^{(\text{hop})}_{N\text{trunc}}(R_t) \) with the average number of MTs per
fiber-connected cell \( N_{MT} \), which is given by [36]

\[
N_{MT} = 1 + 1.28 \frac{\lambda_{MT}}{\lambda_{R}}.
\]  

(54)

D. Insights Regarding the Comparison of \( R_{cov}^{(FD)} (R_t) \) With \( R_{cov}^{(HD)} (R_t) \)

**Proposition 2:** In the unbiased case, i.e. \( B_{BS} = 1 \), \( R_{cov}^{(FD)} (R_t) \) and \( R_{cov}^{(HD)} (R_t) \) asymptotically overlap for \( \lambda_{R}^{(C)} \gg \lambda_{R}^{(W)} \), whereas the maximum performance gain of \( R_{cov}^{(FD)} (R_t) \) over \( R_{cov}^{(HD)} (R_t) \) is attained for \( \lambda_{R}^{(C)} \ll \lambda_{R}^{(W)} \) and \( \sigma_{N}^2 \ll \sigma_{N}^2 \).

**Proof:** For tractability regarding the proof of Proposition 2 and without loss of generality, let us assume that: i) The number of MTs, i.e. \( N_{MT} \), in the case of LOS mmWave propagation is a common assumption in literature and tends to 1 and 0, respectively. Hence, \( \lambda_{R}^{(C)} \ll \lambda_{R}^{(W)} \) and \( \sigma_{N}^2 \ll \sigma_{N}^2 \), according to (56). On the other hand, if \( \sigma_{N}^2 \) is comparable or larger than \( \sigma_{N}^2 \), these gains can reduce considerably and even a point can be reached where \( R_{cov}^{(FD)} (R_t) \) outperforms \( R_{cov}^{(HD)} (R_t) \) as the results of Section V reveal.

E. Average Cost for Fiber-Cable Deployment in an Area

Let us assume that within a land area denoted by \( S_{area} \) an operator has some already deployed fiber-connected RRHs with density \( \lambda_{R}^{(initial)} \). In addition, the operator would like to densify the network by deploying additional fiber-connected RRHs with density \( \lambda_{R}^{(added)} \). The average number of fiber-cable connections per BBU, denoted by \( \bar{R}_{cable}^{(added)} \), required is equal to \( \frac{\lambda_{R}^{(added)}}{\lambda_{BBU}} \). Furthermore, considering the fact that according to our system model the fiber-connected RRHs are associated with their closest BBU, the pdf of the distance \( R_{R(c),BBU} \) between a fiber-connected RRH and a BBU, which we denote by \( f_{R_{R(c),BBU}} (x) \), is given by

\[
f_{R_{R(c),BBU}} (x) = 2 \pi \lambda_{BBU} x \exp \left( -\pi \lambda_{BBU} x^2 \right).
\]  

(58)

Consequently, the average distance value of \( R_{R(c),BBU} \), denoted by \( \bar{R}_{R(c),BBU} \), is given by

\[
\bar{R}_{R(c),BBU} = 2 \pi \lambda_{BBU} \int_{0}^{\infty} x^2 \exp \left( -\pi \lambda_{BBU} x^2 \right) dx = \frac{1}{2 \sqrt{\lambda_{BBU}}}. 
\]  

(59)

Based on the above, if the installation cost per meter of a fiber cable (including design and excavation costs) is equal to \( c_{fiber} \), the total average cost for the fiber connections required between the added fiber-connected RRHs and their associated BBUs in \( S_{area} \), which we denote by \( \bar{C}_{cable}^{(added)} \), is given by

\[
\bar{C}_{cable}^{(added)} = \frac{c_{fiber} S_{area} \bar{R}_{R(c),BBU}^{(added)}}{2 \sqrt{\lambda_{BBU}}}. 
\]  

(60)

V. RESULTS

The aim of this section is twofold: i) To validate, by means of Monte-Carlo simulations, Propositions 1 and 2; ii) To substantiate the tradeoff between the induced cost and performance enhancement achieved by densifying the network with fiber-connected RRHs. Towards this, we use the parameters of Table III. Such a value of \( p \) corresponds to a scenario dense in blockages, such as the one encountered in big cities like Chicago and Manhattan [34]. As far as the simulation setup is concerned, we consider a circular simulation area of radius 2 km and as far as the buildings that act as blockages are concerned, we generate circles of radius \( R_B \) with centers following a PPP of intensity \( \lambda_{Blockages} \). Regarding the fiber-connected and wireless RRHs, if an RRH is generated inside the area occupied by a building we consider that the link

\[\text{considering the value 2, i.e. free-space path-loss, for the path-loss exponent in the case of LOS mmWave propagation is a common assumption in literature works [17, 35].} \]
TABLE III
PARAMETER VALUES USED IN THE SIMULATIONS.

| Parameter | Value |
|-----------|-------|
| $P_R$     | 30 dBm |
| $R_R$     | 0.5   |
| $\lambda_R = \lambda_R^{(W)} + \lambda_R^{(C)}$ | 2 $\frac{\text{dBm}}{\text{m}}$ |
| $\lambda_{MT}$ | 2 $\lambda_R$ |
| $BW$      | 2 GHz |
| $R_B$     | 10 m  |
| $p$       | 0.46  |
| $\theta_{BS}$ | 1 |
| $G_{R_{(C)}}^{(\text{max})}$, $G_{R_{(W)}}^{(\text{max})}$, $G_{R_{(L)}}^{(\text{max})}$ | 20 dB |
| $G_{R_{(C)}}^{(\text{min})}$, $G_{R_{(W)}}^{(\text{min})}$, $G_{R_{(L)}}^{(\text{min})}$ | 0 dB |
| $G_{MT}^{(\text{max})}$ | 8 dB |
| $G_{MT}^{(\text{min})}$ | 0 dB |
| $\theta_{R_{(C)}, \theta_{R_{(W)}}, \theta_{R_{(L)}}}$ | 30° |
| $\theta_{MT}$ | 60° |
| $\alpha_{LOS}^{(R_{(C)}), \alpha^{(R_{(W)})}}$ | 2 |
| $\alpha_{LOS}^{(R_{(C)}), \alpha^{(R_{(W)})}}$ | 4 |
| $\alpha_{KLOS}^{(R_{(C)}), \alpha^{(R_{(W)})}}$ | 3.5 |
| $N_{\text{trunk}}$ | 20 |

between that RRH and any other node is a NLOS link. This is consistent with the simulation-setup considerations in the literature [34].

A. Validation of Propositions 1 and 2

In Fig. 2, we present the $R_{cov}^{(HD)}$ ($R_t$), $R_{cov}^{(FD)}$ ($R_t$) vs. $R_t$ plots for a high and a small ratio of the density of the wireless RRHs over the total density of the RRHs in the network and for a low, moderate, and high value of $\sigma_{2}^{2}$. From Fig. 2, we observe that: i) There is a close match of the analytical model with the simulations for both ratios and for all the $R_t$ regimes. This validates the extracted analytical model, according to Proposition 1 and the noise-limited nature of the network (assumption which the extraction of the analytical model was based on) even for such a high value of $\lambda_R$ (network dense in RRHs) that we consider in this work. Hence, the system designer can readily use this framework to estimate the performance achieved for any ratio of the wireless over the total number of RRHs in the network; ii) The highest difference between $R_{cov}^{(FD)}$ ($R_t$) and $R_{cov}^{(HD)}$ ($R_t$) is achieved for the 70% ratio of the density of the wireless over the total RRH density and adequately high cancellation level of the self interference. In fact, we see that $\sigma_{2}^{2}$ achieves almost the same performance, which means that the need for very high cancellation levels of the self interference can be alleviated. Such trends validate Proposition 2. Such a trend is attributed to the fact that when $\lambda_{R}^{(W)} >> \lambda_{R}^{(C)}$ the communication in the vast majority of cases takes place in 2 hops and, hence, the advantage of FD RRHs becomes more pronounced when $\sigma_{2}^{2}$ is substantially low. On the other hand, if the latter does not hold, a network with HD RRHs will provide better performance than its FD counterpart, as we can see from Fig. 2-(a). Hence, if the density of the wireless RRHs is not much higher than the corresponding one of the fiber-connected RRHs or the self-interference cancellation level cannot be adequately high, for the system designer it might not worth the burden to deploy FD wireless RRHs for achieving a relatively small gain over the HD case. This is due to the fact that the FD functionality requires a careful design regarding the self-interference cancellation part, which is expected to consume additional power regarding the electronic components of the FD nodes.

To further substantiate how the gap of the achieved performance of the FD-based network with respect to its HD counterpart is reduced as the ratio $\frac{\lambda_{R}^{(W)}}{\lambda_{R}^{(C)}}$ increases, in Fig. 3-(a) we illustrate, based on the derived analytical model, the median rate values of the FD and HD networks, which we denote by $R_{50}^{(FD)}$ and $R_{50}^{(HD)}$, respectively, vs. $\frac{\lambda_{R}^{(W)}}{\lambda_{R}^{(C)}}$ for $\sigma_{2}^{2} = \sigma_{N}^{2}$. As expected, the median rate improves for both networks as $\frac{\lambda_{R}^{(W)}}{\lambda_{R}^{(C)}}$ increases. However, the values almost overlap when $\frac{\lambda_{R}^{(W)}}{\lambda_{R}^{(C)}}$ is close to 1. The resulting ratio of $R_{50}^{(HD)}$ over $R_{50}^{(FD)}$ is depicted in Fig. 3-(b), which indicates that this ratio monotonically reduces as $\frac{\lambda_{R}^{(W)}}{\lambda_{R}^{(C)}}$ increases.
B. Tradeoff Between Performance and Cost as λ_{R(C)} Increases

Let us assume that λ_{R(C)}^{(initial)} = 22/km^2. In Fig. 4, we present the performance/cost tradeoff as λ_{R(C)} increases through the increase of the number of fiber-connected RRHs, λ_{R(C)}^{(added)}, that are added in the network. In Fig. 4-(a), as λ_{R(C)} increases we observe the performance enhancement vs. λ_{R(C)}^{(added)}/λ_R, which is the ratio of the density of the added fiber-connected RRHs over the total RRH density. The performance evaluation is in terms of the median-rate gain over the median rate that corresponds to λ_{R(C)}^{(initial)} case. As we observe from Fig. 4-(a), moving to around 50% of RRHs being fiber connected increases the median rate about 10 times compared to the one corresponding to the λ_{R(C)}^{(initial)} case. This is due to the fact that as the density of the fiber-connected RRHs increases, the number of served MTs per fiber-connected RRH decreases. However, the cost to achieve such an enhancement might be substantial, as we observe in Fig. 4-(b) that depicts C_{cable}^{(added)} vs. λ_{R(C)}^{(added)}/λ_R for major cities in the world. The system designer can use such curves to extract the best tradeoff between performance enhancement and cost in scenarios of interest.

C. Suitability of the RRH PPP Modeling

Let us now discuss the suitability of modeling the RRHs as points of a uniformly distributed PPP. Based on such an assumption, at any given realization there is a non-zero probability that 2 generated RRHs are located arbitrarily close to each other. However, in real-world conditions there is a minimum distance of separation between any given pair of RRHs, which originates from their deployment onto structures, such as lampposts. Hence, a more realistic approach would be to model the RRHs as points of a Matérn hard-core point process (MHCPP) of type II with parameter d_{rep}, which is called repulsion and denotes the minimum allowed distance between any RRH pair [46]. Based on this, the question that arises is whether such a consideration would change the key outcomes corresponding to the comparison of the FD with the HD-based network. To answer this, in Figs. 5-(a), 5-(b), and 5-(c) we depict \lambda_R^{(W)}/\lambda_R vs. \lambda_{R(C)} for \sigma^2_{SI} = \sigma^2_N. Regarding \lambda_R^{(W)} vs. d_{rep}, we see that as d_{rep} increases it slightly reduces, which reveals that increasing the repulsion among RRHs has a minor effect on the ratio of the wireless-RRH number over the total RRH number in the network.
However, although the aforementioned ratio remains almost constant the achievable performance in terms of, for instance, $R_{50}^{(HD)}$ and $R_{50}^{(FD)}$, substantially reduces as $d_{rep}$ increases. This is an expected trend due to the dependent thinning that the MHCPP introduces, which increases the average inter-RRH distance. Finally, we see that such a performance loss affects the HD- and FD-based networks, but the relative gain that the latter network achieves over its former counterpart remains almost constant as the repulsion increases. Consequently, such a gain can be extracted by the considered PPP modeling for the RRHs, which simplifies the analytical derivations.

VI. Conclusion

Motivated by the importance of self-fronthauling in future 5G networks, in this work we have provided an analytical study for a C-RAN self-fronthauling architecture where the wireless RRHs are fronthauled through the fiber-connected RRHs. By focusing on the in-band case where the fronthaul and access networks use the same mmWave frequency band and by considering a stochastic-geometry approach for the modeling of the position and number of fiber-connected RRHs, wireless RRHs, and MTs, we have derived an analytical framework for the coverage rate in the downlink. The derived framework incorporates the two possible types of wireless RRHs, namely HD and FD and, according to the results, it exhibits a good match with the Monte-Carlo simulations. In addition, we have analytically proved and validated against the simulations that the maximum rate gain of the FD over the HD case is exhibited if the density of the wireless RRHs is substantially higher than the one of the fiber-connected ones and for an adequately small self-interference power level. On the other hand, if the density of the fiber-connected cells is notably higher than the one of their wireless counterparts, the HD and FD cases asymptotically overlap.

Finally, the tradeoff between performance enhancement and cost as the density of the fiber-connected RRHs increases was examined. Towards this, an analytical estimation of the induced cost was provided that incorporates the area of cities as a parameter. The results show that although the median rate can substantially increase when the network is densified in fiber-connected RRHs, the induced deployment cost of fiber substantially increases for large cities, such as New York and Chicago. These are issues that the system designer, based on our framework, can take into account when deciding about the particular ratio of the wireless-RRH density over the total RRH density that is going to be realized in the network.

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APPENDIX

A. Proof of Proposition 1

According to (38), $R_{cov}^{(1,hop)}(R_t)$ consists of summing $R_{cov}^{(1,hop)}(R_t)$, which corresponds to the coverage rate of single-hop communication, and $R_{cov}^{(2,hop)}(R_t)$, which corresponds to the coverage rate in the two-hop communication. Let us provide a sketch of the proof by indicatively examining $R_{cov}^{(1,hop)}(R_t)$. From (31) and by using (35) for
the noise-limited approximation of $SNR^{(1)}_{R_o^{(c)(1)}, MT_o}$, it holds that

$$P_{cov}(1, hop) (R_t; R_u) \approx \Pr \left[ \left| R_u \right|^2 > \frac{\kappa_o \sigma_N^2 G_{\text{MT}(\mu) \sigma_o}^{\text{max}}}{G_{\text{MT}(\mu) \sigma_o}^{\text{max}}} \times \left( 2 \frac{N_{MT} + R_u}{R_u} - 1 \right) \left| R_u \right| \right] \times \frac{\left( 1 - K_R \right) G_{\text{MT}(\mu) \sigma_o}^{\text{max}}}{B_{BS} G_{\text{MT}(\mu) \sigma_o}^{\text{max}}} \left( \frac{\left| R_u \right|^2}{\sigma_{o_2}^2} \right) \left( \frac{\left| R_u \right|^2}{\sigma_{o_2}^2} \right) \left| R_u \right|$$

There are 4 possible cases of the links $R_o^{(c)(1)} - MT_o$ and $R_o^{(W)} - MT_o$ that are involved in (61) being both LOS, one LOS and the other NLOS, or both NLOS. In addition, given that the link between $MT_o$ and $R_o^{(c)(1)}$ or $R_o^{(W)}$ is LOS or NLOS the corresponding probability density functions of the link distances $R_o^{(c)(1)}$ and $R_o^{(W)}$ are given by [17, Eq. (6)] and [17, Eq. (7)], respectively. Taking these into account, (39) is obtained.

The same process is used for the derivation of $R_{cov}^{(1, hop)} (R_t)$ by assuming that $R_{R_o^{(c)(1)}}^{(W)}$ and $R_{R_o^{(W)}}^{(2, hop)} (R_t)$ are independent.

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