WHITE PAPER
5G Wireless Communications
Silicon Photonics

Exploring 5G Fronthaul Network Architecture Intelligence Splits and Connectivity

This paper examines centralized and distributed network architecture intelligence splits and identifies areas where Intel® Silicon Photonics can meet demanding bandwidth requirements

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Executive Summary

Wireless networks are evolving quickly as they experience ever-increasing traffic and as they connect to more devices. There is a pressing need for increased bandwidth and range as well as decreased latency and cost, as the industry prepares for the arrival and scaling of 5G networks. In many cases, networks are becoming less centralized and more complex, placing increased demands on the fronthaul network. In this paper, fronthaul refers to the connection from the cell site antenna to the central office where the baseband unit is housed, with the option for distributed units (DUs) with added intelligence processing closer to the antenna (see Figure 2 on page 3).

To meet the need for increased capacity and low latency, while also managing costs, network architects and engineers face many options and trade-offs, particularly with respect to how much intelligence to place at the remote radio head (RRH) versus in a centralized location. There is no one-size-fits-all solution. Even within the same carrier network, different topologies may be deployed to meet the unique needs of different regions, and all of these are supported by Intel's FlexRAN reference implementation.

This paper presents and evaluates varying centralized versus distributed 5G fronthaul network topologies, the connectivity requirements for each, and explains where Intel® Silicon Photonics optical transceivers—an innovative combination of lasers and silicon-integrated optical circuits that can be manufactured in high volume at wafer scale—offer an attractive solution to meet the high bandwidth and distance requirements associated with critical links in these topologies.

Contributor

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Acronyms

3GPP	3rd Generation Partnership Project (3gpp.org)
BBU	baseband unit
BW	bandwidth
CWDM4	Coarse Wavelength Division Multiplexing technology with 4 lanes
cmWave	centimeter-wave (3-30 GHz frequency spectrum, where wavelength is measured in centimeters)
CPRI	Common Public Radio Interface (industry collaboration, see cpri.info)
CRAN	centralized radio access network
CU	centralized unit
DRAN	distributed radio access network
DU	distributed unit
FlexRAN	Intel's 4G/5G vRAN reference implementation
Gbps	gigabits per second
IoT	Internet of Things
MIMO	multiple-input, multiple-output
mmWave	millimeter-wave (30-300 GHz frequency spectrum, where wavelength is measured in millimeters)
O-RAN	Open RAN Alliance (industry consortium); a merge of xRAN Forum and CRAN Forum
QSFP	Quad Small Form-factor Pluggable
RAT	radio access technology
RRH	remote radio head
SCS	sub-carrier spacing
TIP	Telecom Infra Project (industry consortium, see telecominfraproject.com)
vRAN	virtualized radio access network
xRAN	extensible Radio Access Network (xRAN) Forum (industry consortium, see xran.org)

Introduction

It is estimated that by 2020 there will be 20 billion Internet of Things (IoT) connections.[1] Additionally, global mobile data traffic will increase sevenfold between 2016 and 2021, growing at a compound annual growth rate (CAGR) of 47 percent from 2016 to 2021, reaching 49 exabytes per month by 2021.[2] Most of this traffic will be video streaming[2] along with new use cases such as augmented reality, virtual reality, and machine-to-machine communications. The current 4G network doesn't have the capacity to gracefully handle this explosion of traffic.

5G networks are targeting an approximately 1000x increase in wireless traffic capacity.[3, 4] This additional capacity will enable major advances in smart cities, smart grids, robust disaster response, self-driving cars, and more. In addition to increased capacity, compared to 4G, 5G networks can deliver increased data rates (around 100x higher), reduced latency (less than 1 ms), reduced energy requirements, and more reliable connectivity.[5] As wireless networks develop to meet the needs of 5G, these networks will become faster, smarter, and more complex.

Wireless carriers and telco equipment manufacturers are preparing for the increased demands of 5G in three main ways:

- Improving spectral efficiencies by using sub-6 GHz frequencies for emerging IoT devices and centimeter-wave (cmWave) and millimeter-wave (mmWave) for data transfer at frequencies up to 300 GHz.
- Developing small-cell networks, contributing to network densification, that will support faster speeds and a greater diversity of devices.
- Building multiple-input multiple-output (MIMO) antennas with 10s or 100s of elements per antenna and beamforming, both of which enable one antenna to better serve a wider range of users and use cases.

5G networks will be diverse architecturally, geographically, and vertically in the devices and use cases they support (see Figure 1). One constant, however, will be increased demand on the fronthaul network, which will play a larger role as networks become less centralized and more complex.

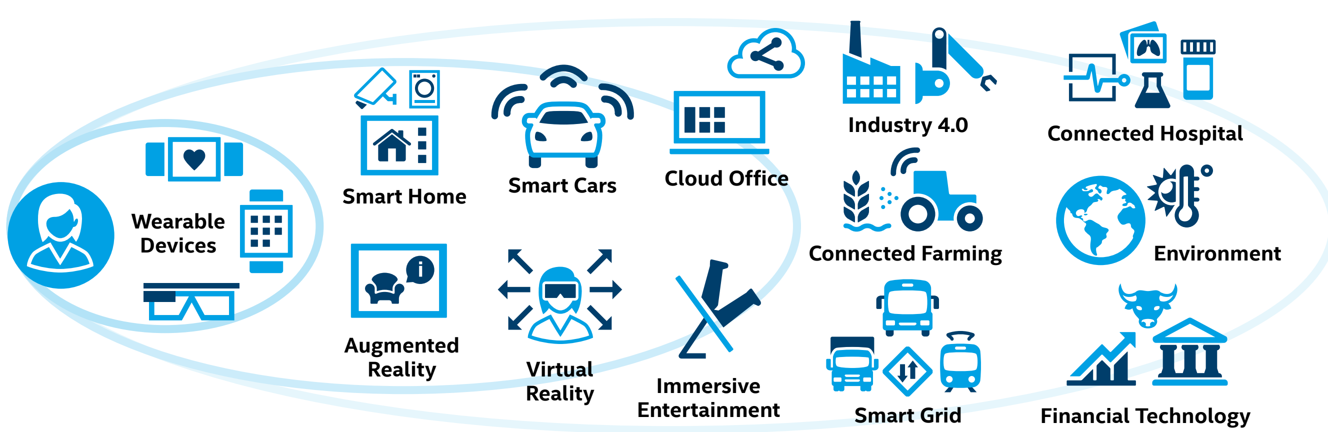

Figure 1. Diverse 5G network use cases.

Intel® Silicon Photonics Optical Transceivers for 5G Fronthaul Networks

Intel® Silicon Photonics optical transceivers are an innovative on-die integration of a silicon circuit and a laser. Intel Silicon Photonics optical transceivers are expected to become an important part of 5G fronthaul networks because they support high bandwidth rates, long transmission distances (up to 10 km), and extended temperature ranges (-40° to 85° C as opposed to 0° to 70° C for standard commercial-grade transceivers).[6] Intel Silicon Photonics can also be used effectively in 4G fronthaul networks that have transitioned from copper connectivity to fiber optics. Intel Silicon Photonics modules take full advantage of the greater bandwidth potential of fiber, with current transmission rates up to 100 Gbps with high spectral efficiency by multiplexing four 25 Gbps wavelengths onto a single fiber.

As seen in Figure 2, Intel Silicon Photonics optical transceivers can be used across diverse 5G networks in locations including:

- Connections between remote radio head (RRH) and baseband unit (BBU) in a distributed unit (DU) or central office
- Connections between the centralized unit (CU) and the DU or switches
- Connections between switch and small-cell radio access points
- High-speed connections within the data center

Functional Split Options for 5G Networks

As network architects work to meet the 5G challenges of increased traffic and data flows, a fundamental question is how much intelligence to put near the antenna versus at the DUs or CUs. Wireless carriers as well as industry-standards groups, such as the 3rd Generation Partnership Project (3GPP), IEEE, Telecom Infra Project (TIP), and O-RAN, have been rethinking network architectures. One overarching question is how to partition functional splits to best provision diverse 5G networks.

Many fronthaul connections use the Common Public Radio Interface (CPRI) connection protocol, which has been used mainly for point-to-point transport for macro base stations. Because of the increase in scale of 5G, a more efficient fronthaul interface is needed. As industry bodies consider new network architectures, a key consideration is the functional split that separates layers between the BBU and the RRH. The basic question is how much compute to put at the BBU as opposed to at the RRH. The answer depends on the use case.

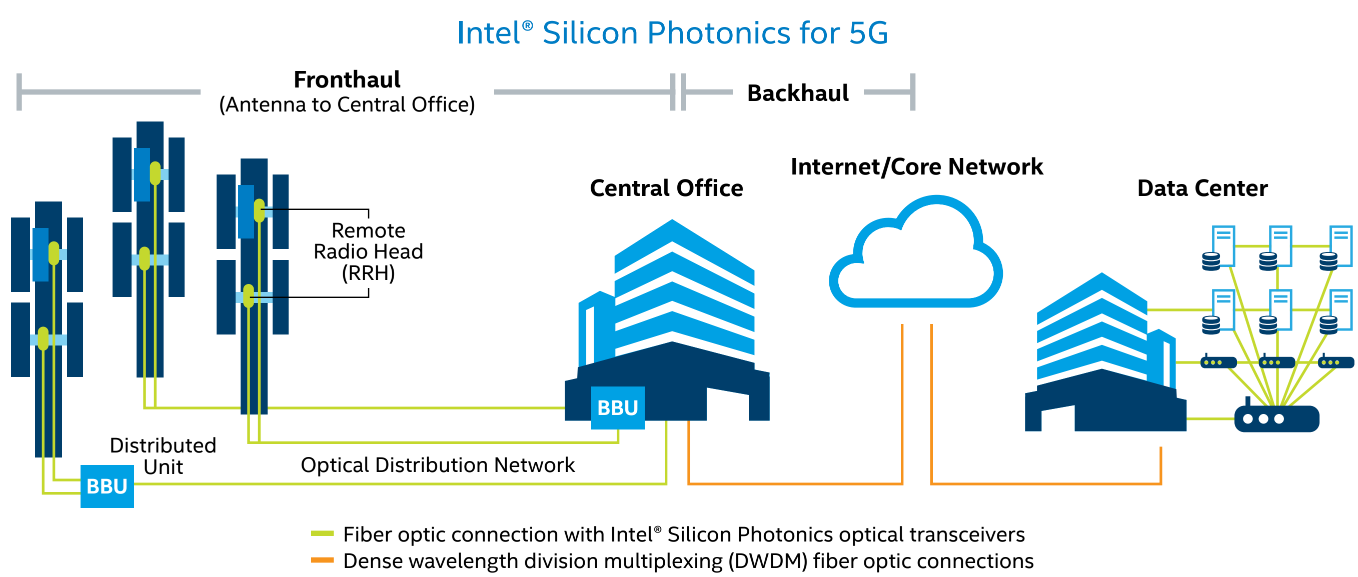

Figure 2. Intel® Silicon Photonics optical transceivers can be used across 5G networks.

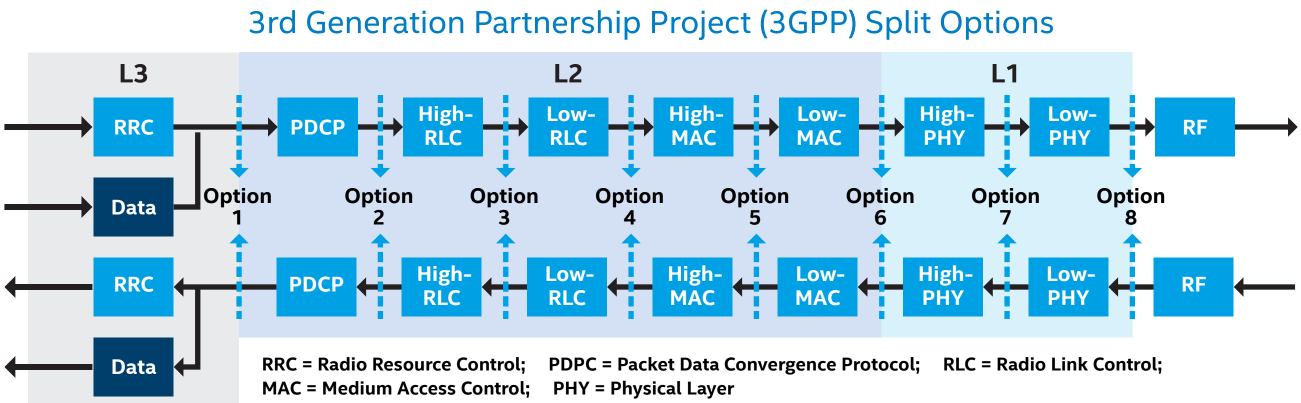

Figure 3. 3GPP split options allow for flexibility, scaling, and potential cost savings (source: **TR 38.801**). Functions to the left of each split option are handled by the baseband unit (BBU) and functions to the right are handled by the remote radio head (RRH).

3GPP has defined eight functional split options for fronthaul networks in Technical Report 38.801 (see Figure 3). With an option 2 split, for example, some Layer 2 (L2) Ethernet functions can reside in the RRH and there is the possibility that aggregation and statistical multiplexing can be done before the data is passed across the fronthaul network. This greatly reduces the amount of data transmitted across the interface. On the other hand, with an option 7 split, some Layer 1 (L1) functions can reside in the BBU and pooling gains can be realized with centralized processing.

Intel supports activities that help enable the industry to innovate and adapt on virtualized radio access network (vRAN) efforts that utilize flexible architectures, like Intel's FlexRAN reference implementation. This solution fits well with 3GPP split options and can help enable fronthaul bandwidth efficiency. With this approach, the functional splits offer flexibility, allowing the implementation to be scaled and cost effective, given the network's particular requirements. For these network split approaches to work, BBU and RRH manufacturers must coordinate their efforts. Bandwidth requirements are another important consideration; additional components may be necessary to meet larger bandwidth requirements. Therefore, the cost of a BBU versus the cost of an RRH may vary depending on the amount of fronthaul functionality on either side of the fronthaul link.

Configurable splits offer the potential to adapt a network architecture to fit particular use cases and requirements, so that it will deliver the desired speed, latency, and throughput. Split option 7 (particularly xRAN 7-2x) keeps the costs of the RRH low. Split option 2 places complexity in the RRH and increases its cost. Another benefit of option 7 (xRAN 7-2x) is that it minimizes the impact on the RRH to changes of the 3GPP specs.

The architectures in Figure 4 show distributed radio access network (DRAN) examples where the BBU is either fully integrated at the tower or integrated at a distribution site at or near the tower, and centralized radio access network (CRAN) examples showing partially centralized RAN and fully centralized vRAN. These architectures can be used for 4G and 5G, across multiple radio access technologies (RAT), and are band-agnostic (able to operate across multiple bands), ranging from sub-6 GHz to mmWave.

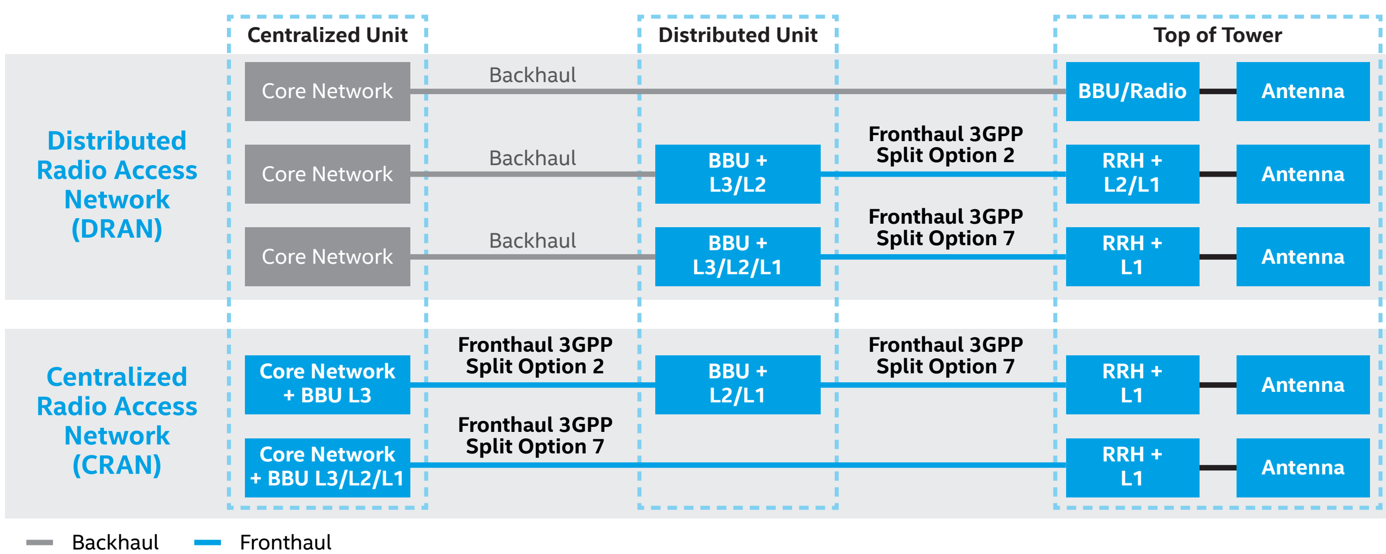

Figure 4. Examples of several 5G deployment models.

Reference Architectures

The following sections consider some common reference architectures supported by Intel's FlexRAN solution in greater detail. These reference architectures are also being considered by industry bodies such as O-RAN and TIP. For each, it is noted where Intel Silicon Photonics optical transceivers can deliver needed performance with high-speed optical data transmission.

The example architectures are as follows:

- DRAN
- Partially centralized RAN
- Fully centralized vRAN
- Small-cell deployments
  - Small-cell CRAN using sub-6 GHz carriers
  - Small-cell partially centralized RAN using mmWave carriers

DRAN

This 5G DRAN deployment example shows an architecture using either an option 2 or option 7 extensible Radio Access Network (xRAN) split for sub-6 GHz, where the DU can be at or near the antenna site (see Figure 5). The DU connects to RRHs that could be anywhere from a few meters to 10 km from the DU, and the BBU/RRH workloads are split accordingly.

If a bandwidth of 100 MHz using a sub-carrier spacing (SCS) of 60 kHz is assumed, then a 3-sector antenna using a single carrier with a 4x4 antenna arrangement would require around 34 Gbps fronthaul capacity across an option 7 split, while an 8x8 arrangement would require around 67 Gbps (see Table 1). Currently offering up to 100 Gbps bandwidth, Intel® Silicon Photonics 100G CWDM4 QSFP28 Extended Temperature Optical Transceivers are an ideal solution for the fronthaul network. Note that the option 2 split fronthaul requirement capacity is much less, requiring a lower-capacity optical link.

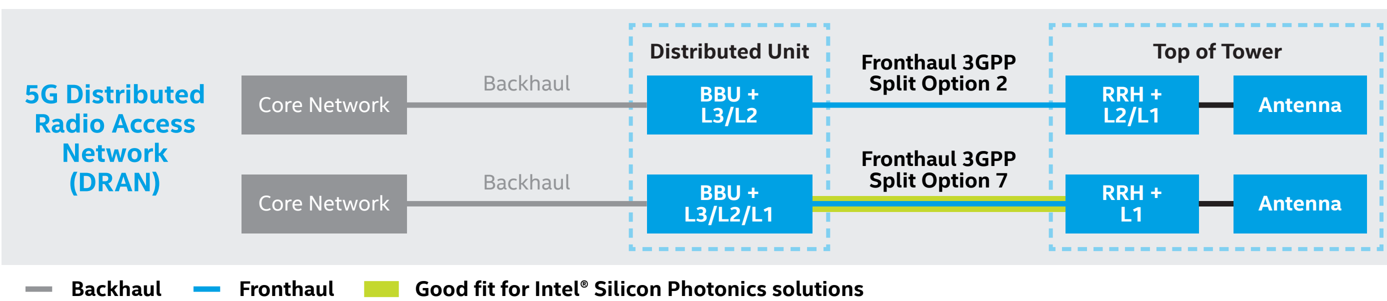

Figure 5. 5G distributed radio access network example architecture.

Table 1. 5G Sub-6 GHz Configurations for Distributed Radio Access Network and Partially Centralized Radio Access Network

5G Deployment (sub-6 GHz configurations)	Bandwidth (BW) and Numerology	3GPP Split Option 2 Fronthaul Rate Estimates	3GPP Split Option 7 Fronthaul Rate Estimates
5G: macro; 4x4 MIMO 3-sector, 1 carrier	BW = 100 MHz SCS = 60 kHz (u=2)	~4 Gbps	~34 Gbps
5G: macro; 8x8 MIMO 3-sector, 1 carrier	BW = 100 MHz SCS = 60 kHz (u=2)	~8 Gbps	~67 Gbps

SCS – sub-carrier spacing MIMO – multiple-input, multiple-output

Partially Centralized RAN

This 5G CU/DU deployment example shows an architecture that uses split option 2 between the CU and DU (see Figure 6). This part of the fronthaul network can be connected to an Ethernet gateway that is connected to multiple DUs. The DU to RRH link uses split option 7 (xRAN) and the fronthaul capacity requirements for a sub-6 GHz, 3-sector site using 100 MHz of bandwidth and a SCS of 60 kHz are around 34 Gbps for a 4x4 arrangement and 67 Gbps for an 8x8 arrangement (see Table 1). Intel Silicon Photonics optical transceivers are an excellent fit for the DU to RRH connection with split option 7 in this architecture. System designers can choose between commercial-temperature and extended-temperature versions of these transceivers, depending on the implementation.

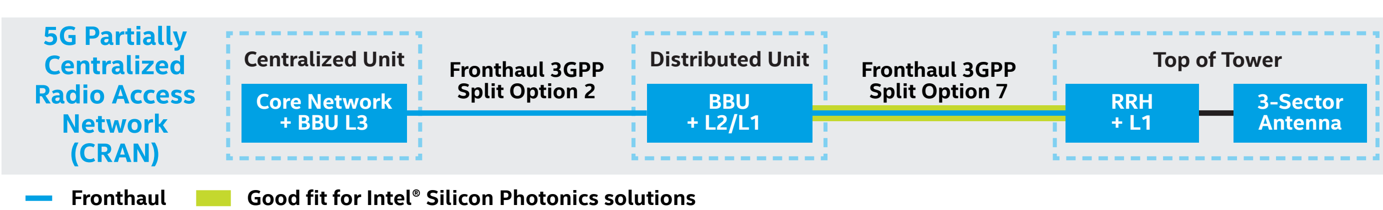

Figure 6. 5G Partially centralized radio access network.

Fully Centralized vRAN

This 5G vRAN deployment example shows the BBU fully centralized (see Figure 7). L1 functions are split between the BBU and the RRH, and fronthaul split option 7 (xRAN) is used. Multiple antenna sites are connected to the centralized BBU using a switching point in the network. Each antenna site has three sectors and a single carrier. Intel Silicon Photonics optical transceivers can handle the high bandwidth required for this architecture. System designers can choose between commercial-temperature and extended-temperature versions of these transceivers, depending on the implementation. See Table 2 for the fronthaul rate estimates for this architecture. To accommodate the fronthaul rate, multiple lanes of 100 Gbps may be used.

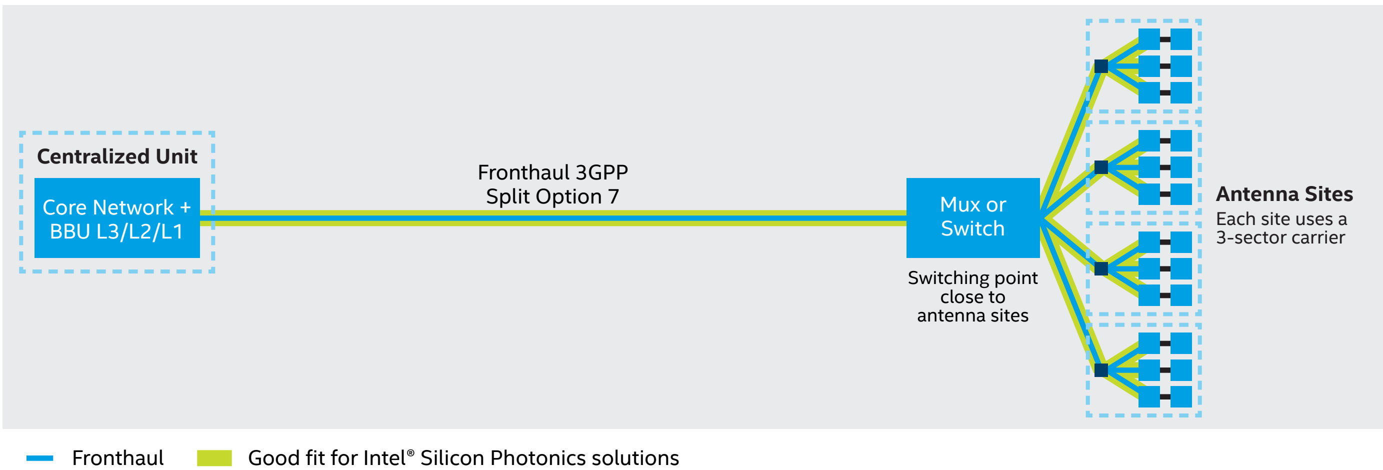

Figure 7. Fully centralized virtualized radio access network (vRAN).

Table 2. 5G Sub-6 GHz Configurations for Virtualized Radio Access Network (vRAN)

5G Deployment (sub-6 GHz configurations)	Bandwidth (BW) and Numerology	3GPP Split Option 7 Fronthaul Rate Estimates (Centralized Unit to Mux)	3GPP Split Option 7 Fronthaul Rate Estimates (Mux to Each Antenna Site)
5G: macro; 4x4 MIMO 3-sector, 1 carrier	BW = 100 MHz SCS = 60 kHz (u=2)	~134 Gbps	~34 Gbps (~12 Gbps/sector)
5G: macro; 8x8 MIMO 3-sector, 1 carrier	BW = 100 MHz SCS = 60 kHz (u=2)	~267 Gbps	~67 Gbps (~23 Gbps/sector)

SCS – sub-carrier spacing **MIMO – multiple-input, multiple-output** **mux – multiplexer**

Small-Cell Deployments

Small-cell deployments can be installed in venues such as stadiums, shopping malls, railway stations, and streets, as well as in office buildings where there is a high concentration of users or where short-wavelength mmWaves have difficulty transmitting around or through buildings, walls, or other obstacles. Often, edge compute is used for the CU that is placed relatively close to the antenna sites where a venue's server facility might be used for the CU, and a backhaul connection is used to connect to the core network. The CU may connect to multiple RRHs that might be distributed around the venue or location, and switches/routers may be used as switching points.

Small-Cell CRAN Using Sub-6 GHz Carriers

This small-cell deployment example uses a centralized architecture that is connected to multiple antenna sites (see Figure 8). Each antenna uses a MIMO single-sector, single-carrier arrangement, and requires a split option 7 (xRAN) interface. Intel Silicon Photonics 100G CWDM4 QSFP28 Optical Transceivers can be used for both the link between the CU and the switch, and between the switch and the antennas. See Table 3 for the fronthaul rate estimates for this architecture. To accommodate the fronthaul rate, multiple lanes of 100 Gbps may be used.

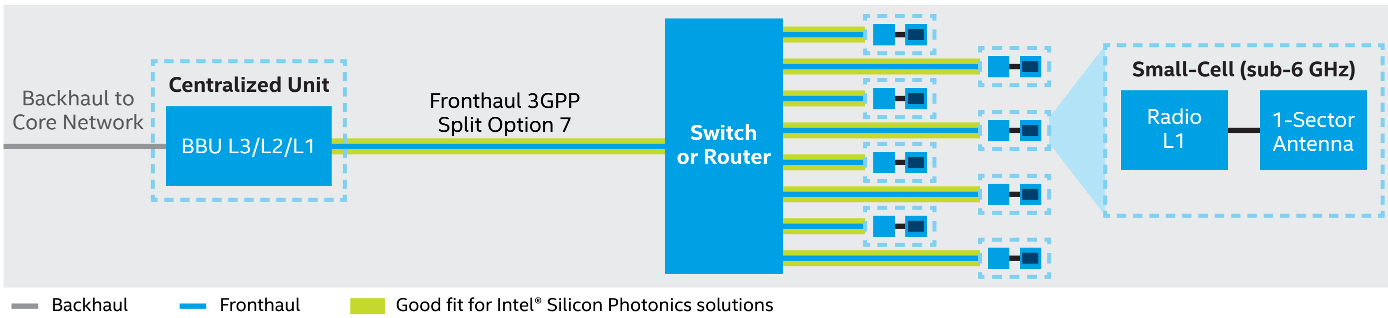

Figure 8. Small-cell deployment example using sub-6 GHz and eight antenna sites.

Table 3. 5G Sub-6 GHz Configurations for Small-Cell Deployment

5G Deployment for 8-Antenna Sites (sub-6 GHz configurations)	Bandwidth (BW) and Numerology	3GPP Split Option 7 Fronthaul Rate Estimates	Fronthaul Rate Estimate per Antenna Site
5G: small-cell; 4x4 MIMO 1-sector, 1 carrier	BW = 100 MHz SCS = 60 kHz (u=2)	~89 Gbps	~12 Gbps
5G: small-cell; 16x16 MIMO 1-sector, 1 carrier	BW = 100 MHz SCS = 60 kHz (u=2)	~355 Gbps	~45 Gbps

SCS – sub-carrier spacing MIMO – multiple-input, multiple-output

Small-Cell Partially Centralized RAN Using mmWave Carriers

This small-cell deployment example uses a partially centralized architecture that is connected to multiple antenna sites that deploy advanced antenna systems, such as antenna arrays with beamforming (see Figure 9). This system may be used in dense urban deployments with high numbers of active users. Each site uses a single carrier with a multiple-array antenna and has a high amount of BBU functionality at the antenna site. Split option 2 is used across the fronthaul. A switch is used to distribute the fronthaul to each antenna site. Intel Silicon Photonics optical transceivers can handle the high bandwidth required for this architecture. System designers can choose between commercial-temperature and extended-temperature versions of these transceivers, depending on the implementation. See Table 4 for the fronthaul rate estimates for this architecture. To accommodate the fronthaul rate, multiple lanes of 100 Gbps may be used.

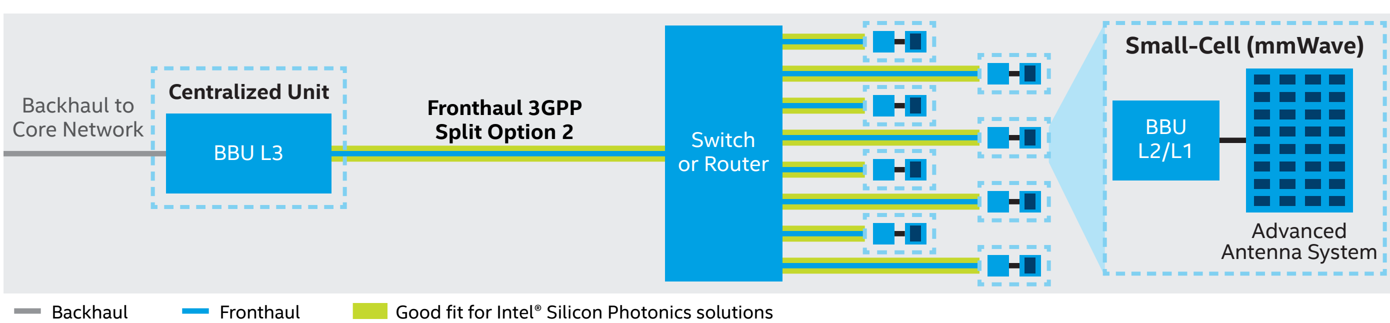

Figure 9. Small-cell deployment example using millimeter-wave multiple-array antennas.

Table 4. Millimeter-Wave Configurations for Small-Cell Deployment

5G Deployment for 8-Antenna Sites (mmWave configurations)	Bandwidth (BW) and Numerology	3GPP Split Option 2 Fronthaul Rate Estimates (CU to Switch or Router)	Fronthaul Rate Estimate per Small-Cell Site (Switch or Router to Small Cell)
5G: small-cell; 64x64 array panel 1-sector, 1 carrier	BW = 100 MHz SCS = 120 kHz (u=3)	~309 Gbps	~39 Gbps
5G: small-cell; 128x128 array panel 1-sector, 1 carrier	BW = 100 MHz SCS = 120 kHz (u=3)	~618 Gbps	~78 Gbps

SCS – sub-carrier spacing CU – centralized unit

Benefits of Intel® Silicon Photonics Optical Transceivers

The use case examples discussed previously and summarized below (see Table 5) have demonstrated that the fronthaul rate requirements for 5G will be demanding, even after accounting for some improved efficiencies compared to CPRI.

In numerous cases Intel Silicon Photonics can help meet 5G fronthaul network requirements. Intel Silicon Photonics optical transceivers provide:

- High bandwidth, with transmission rates up to 100 Gbps
- An extended temperature range (-40° to 85° C as opposed to 0° to 70° C for standard commercial-grade transceivers) for extreme outdoor deployments
- Long transmission distances (up to 10 km)

Intel Silicon Photonics employs the only hybrid laser approach in the industry, where the light-emitting capability is integrated with silicon at the wafer level. This approach removes the need for optical alignment and results in a manufacturing process that leverages Intel's high-volume silicon production capabilities, with significant performance, cost, and scale benefits.

Intel Silicon Photonics optical transceivers also support multiple industry standards and enable network function virtualization and software-defined infrastructure, creating flexible network architecture and simple network maintenance.

Industry Alliances and Organizations

Multiple industry groups are working on 5G deployments and standards. These groups include:

- Common Public Radio Interface (CPRI): A consortium of original equipment manufacturers (OEMs) working together to define specifications for key internal interfaces for radio base stations in mobile networks.
- O-RAN Alliance: A group of telecom companies focused on fostering wireless networks that are open software defined and virtualized, enabling architects to mix and match products from different vendors. In 2018, the xRAN and C-RAN organizations merged to form O-RAN.
- Telecom Infra Project (TIP): A collaboration between operators, suppliers, integrators, and startups seeking to drive innovation across the telecom landscape.
- 3rd Generation Partnership Project (3GPP): Unites several telecommunications standard development organizations and provides their members with a stable environment to produce the reports and specifications that define cellular telecommunications network technologies, including radio access, the core transport network, and service capabilities.

Table 5. Fronthaul Rate Summary for Some Simple Use Cases

Deployment	Carrier	Bandwidth (BW) and Numerology	Split Option 2 Fronthaul Rate Estimates	Split Option 7 Fronthaul Rate Estimates
5G: macro; 4x4 MIMO, 3-sector, 1 carrier	Sub-6 GHz	BW = 100 MHz; SCS = 60 kHz (u=2)	~4 Gbps	~34 Gbps (~12 Gbps/sector)
5G: macro; 8x8 MIMO, 3-sector, 1 carrier	Sub-6 GHz	BW = 100 MHz; SCS = 60 kHz (u=2)	~8 Gbps	~67 Gbps (~23 Gbps/sector)
5G: small-cell; 4x4 MIMO, 1-sector, 1 carrier	Sub-6 GHz	BW = 100 MHz; SCS = 60 kHz (u=2)	~2 Gbps	~12 Gbps (~89 Gbps/switch for 8 antenna sites)
5G: small-cell; 16x16 MIMO, 1-sector, 1 carrier	Sub-6 GHz	BW = 100 MHz; SCS = 60 kHz (u=2)	~6 Gbps	~45 Gbps (~355 Gbps/switch for 8 antenna sites)
5G: small-cell; 64x64 array panel, 1-sector, 1 carrier	mmWave	BW = 100 MHz; SCS = 120 kHz (u=3)	~39 Gbps (~309 Gbps/switch for 8 antenna sites)	–
5G: small-cell; 128x128 array panel, 1-sector, 1 carrier	mmWave	BW = 100 MHz; SCS = 120 kHz (u=3)	~78 Gbps (~618 Gbps/switch for 8 antenna sites)	–

SCS – sub-carrier spacing   MIMO – multiple-input, multiple-output

Conclusion

As mobile networks grow and evolve to meet current 4G LTE demands and welcome the arrival of 5G, a variety of architectural options exist for splitting the protocol functions. Regardless of which option is chosen, there are a number of high-bandwidth connections that can benefit from the use of Intel Silicon Photonics optical transceivers. These transceivers function over long distances (up to 10 km) and have extended temperature ranges (-40° to 85° C), making them well-suited for bridging greater distances between network connection points and outdoor antenna deployments. Perhaps most importantly, Intel Silicon Photonics optical transceivers support bandwidth rates of up to 100 Gbps, allowing network architects to take full advantage of existing or planned fiber optic connections and to create larger massive MIMO antenna arrays, spectrum expansion to sub-6 GHz and mmWaves, and network densification through the use small cells.

For a quick summary of the concepts in this white paper to help guide conversations and decisions with your team about preparing your infrastructure for 5G, get the briefing sheet, **Delivering the Fronthaul Performance Required for Virtualized RAN**.

Intel® Silicon Photonics—A Closer Look

Intel® Silicon Photonics is the result of more than a decade of research and development. Production shipments for Intel's 100G optical transceivers commenced with PSM4 products for data center deployment in 2016. In 2017, the portfolio was expanded to include 100G CWDM4 transceivers. In 2018, Intel Silicon Photonics received the SEMI Americas Award for the First High Volume Integrated Silicon Photonics Transceiver[7] and passed the production-run-rate milestone of more than a million units per year. Also in 2018, Intel expanded the product portfolio to include extended temperature versions for 5G wireless fronthaul deployments and began sampling 400G products for next-generation data center applications. Continued rapid growth is expected as Intel Silicon Photonics further expands into new markets, including automotive light detection and ranging (LIDAR).

Learn More

You may find the following resources useful:

- Intel Silicon Photonics Overview
- Intel Silicon Photonics Optical Transceivers
- Intel Silicon Photonics: From Research to Product
- Intel 5G Press Kit
- Three Ways 5G Technology Will Change Your Life video
- An Overview of FlexRAN video

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