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Architect’s role to improve in-building wireless coverage

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Abstract: This paper investigates the role of architects in improving in-building wireless coverage, a hitherto unexplored and interdisciplinary domain. While architects are still fully focused on built spaces, in this modern era, the attention of the occupants is gradually being influenced by the virtual surrounds, created by wirelessly connected electronic devices, compared to the quality of actual built spaces, they have around them. The rapid growth of internet usage and related technology is bringing a new demand for building occupation—improved wireless connectivity. This paper presents an in-depth analytical discussion of the challenges of in-building wireless signal coverage. It further elaborates on the additional complexities for support at high frequencies. However, studies show that the nature of the space and its bounding surfaces have a direct influence on signal propagation, and thereby, reception. Therefore, this paper proposes architectural interventions to improve in-building wireless coverage and highlights its necessity. In this process, it proposes a collaboration between radio frequency (RF) engineers and architects, during the design phase of buildings. Considering the scope of architectural design, some guidelines are proposed for the architectural interventions, and the possible outcomes of the interventions are discussed. The improvement in user data rate

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PUBLIC INTEREST STATEMENT

This paper investigates the role of architects in improving in-building wireless signal coverage. It discusses the challenges of in-building wireless coverage, along with the additional complexities for support at high frequencies, a major candidate for 5G cellular technology. It proposes architectural interventions to improve in-building wireless coverage. A collaboration between radio frequency (RF) engineers and architects is proposed. Specifically, several guidelines are proposed for an architect. The possible benefits of these proposals are shown to support of higher data rate, coverage in necessary locations, higher number of IoT devices, and IoT devices at deeper locations in buildings; longer battery lives of IoT devices, reduced spillage of signal outside the building, reduced health hazard with 5G, and so forth. For one of the proposed solutions that addresses near-far problem, a common RF issue, the expected outcome is demonstrated using a MATLAB-based numerical analysis, along with necessary theoretical derivations.
experience, from one of the proposed architectural solutions, has also been investigated using MATLAB-based simulation, along with necessary derivations. The paper, thus, aims to pave the way for farsighted contributions to in-building wireless coverage, from architects, so that buildings can better cope with the demands of the future.

**Subjects: Communication Networks & Systems; Digital & Wireless Communication; Electromagnetics & Communication; Architecture**

**Keywords: In-building wireless connectivity; building internet of things (BIoT); in-building solutions (IBS); 5G cellular communication; open planning**

### 1. Introduction

Architects through their very training are problem solvers. The response of architects towards new paradigms in society, towards shifts in values, towards changes in technologies and building systems, new materials, etc., has generated new ways of looking at the very art of architecture (Ahmed, 0000). The modernists came up with various movements generated in the Bauhaus, and beyond it, which shaped the architecture of the twentieth century, a direct response to the needs of the post-war democratization of societies. Subsequent movements, responding to changes in lifestyle, threats to the planet, etc., have seen yet new forms of architecture, stemming from post-modernism, to hi-tech, to phenomenology, etc., in architecture, to name just a handful of paradigm shifts. This paper addresses one of the newest demands of technology that is likely to impact lifestyles, and indeed shape the spaces that we inhabit, to efficiently make use of the latest potentials available to mankind—in-building wireless connectivity.

The rapid growth of wireless use in buildings is propelling the advent of many new applications, making the use of smartphones or other electronic devices, transferring data wirelessly at an increasingly higher rate, one of the key engagements of occupants. From the way the field is developing, it is clear that the Building Internet of Things (BIoT), mostly with wireless connectivity, is going to flood into modern or future buildings, many of which are categorized as smart buildings. In the course of time, apart from the building infrastructure, the performance of wireless communication is finding more direct bearing on the satisfaction level of users of the building. Up until now, this domain has been dominated only by RF engineers, who work on improvement of the performance of wireless communication by ensuring good RF signal strength at the receiver (Rappaport, 2001).

Traditionally, architects focus on aesthetics, environmental concerns, including light, temperature, sound, airflow, views, and so forth, in their building design. However, it is clear that signal coverage is significantly dependent on the nature of the space and its bounding surfaces (Rappaport, 2001), which is the direct responsibility of the architect. Therefore, contributions from architects could ease the job towards ensuring proper wireless coverage and connectivity. Architects and RF engineers can complement each other to address the growing challenge better. Thus, it is now time to add wireless signal coverage to the list of architectural concerns. This is all the more imperative since the building will undoubtedly last much more than a few decades, and should thus be ready for the rapid changes that are predicted in the wireless support arena. However, to the best of our knowledge, architects have not truly engaged in this area so far and some analytical discussions have only been made in this regard (Waldman, 2019). In this paper, the need for architectural interventions has been highlighted and discussions, proposals, and analyses have been presented with regard to the engagement of architects.

The remainder of the paper is outlined as follows. Section II discusses the RF technologies available for in-building wireless connectivity. Section III investigates the growing use of high frequencies in buildings and its impact. Section IV derives the growing challenges of in-building wireless coverage in
an attempt to clarify the architectural interventions needed. In Section V, preliminary guidelines have been proposed for an architect to help improve in-building wireless coverage through design. The necessity of collaboration, between RF engineers and architects, is highlighted. The discussions are augmented by proposing an architectural solution to the near-far problem in buildings, a common RF issue. The possible benefits of the proposed architectural interventions are also discussed. In Section VI, using a MATLAB-based numerical analysis, along with necessary theoretical derivations, the expected outcome of the proposed solution to the near-far problem, is demonstrated for high frequencies, considering 5 G technology. Finally, the whole paper is concluded in Section VII.

2. RF technologies for in-building wireless coverage

This section briefly discusses the RF technologies that can be used to provide in-building wireless connectivity and architects need to be conversant with these technologies in order to engage in the relevant issue. The platform for wireless connectivity in buildings can have three classes as described below.

(1) **Outside Base Station**: The cellular communication system has an inbuilt spatial connotation that splits the geographical area into a number of cells, and each cell is served by a base station. A cell is referred to as macrocell or microcell if the cell size is large or medium, respectively. A building can be pervaded by signal from a cellular base station, located outside the building.

The base station can also be employed only for the specific support of Internet of Things (IoT), and in this regard, three competing platforms, namely, Sigfox, Long Range (LoRa), and Narrowband Internet of Things (NB-IoT) have become popular. Here, Sigfox and LoRa are two proprietary technologies from companies whereas NB-IoT is the development from 3GPP as a feature of the conventional 4 G/5 G cellular system. All these technologies operate at low data rate and low power, and thus, match the requirements of most of the IoT devices. Sigfox and LoRa use unlicensed industrial, scientific, and medical (ISM) radio bands. On the other hand, NB-IoT is a feature of the conventional 4 G/5 G cellular system, and so, it uses the licensed bands. At present, NB-IoT is more expensive compared to Sigfox and LoRa (Mekkia et al., 2019). However, the cost of NB-IoT will gradually decrease, and it will emerge with many advantages (5G Americas, 2019).

(2) **In-Building Solutions (IBS)**: The cellular service can be generated inside the building using an in-building solution (IBS). This is primarily used for large buildings, where proper wireless coverage can be very difficult with signal from the outside base station, due to heavy penetration losses. IBS can be of the following types (The HetNet Forum, 2013).

   (i) **Femtocells**: Femtocells are very small cellular base stations, designed for use within residential buildings, and in small commercial buildings or premises.

   (ii) **Picocells**: Picocells are small cellular base stations, suited for small and medium-sized buildings and premises.

   (iii) **Distributed Antenna System (DAS)**: DAS provides efficient distribution of wireless connections inside large buildings, by routing signals through cables, from a single small base station to multiple antennas, located throughout the building.

(2) **Small Source in the Building**: A number of solutions exist, which use small devices to generate wireless service in the building. However, these small devices are often connected to the outside cellular base stations, for backhaul. These solutions include Wi-Fi, Zigbee, Bluetooth, Z-Wave, and Thread (Pradeep et al., 2016). These solutions differ in their capabilities, costs, and popularities. Besides, WiGig is introduced for a very high data rate and it uses high frequency, which is around 60 GHz (Chakkravarthy et al., 2019).

The IBS allows the use of wireless service inside the building from the same operator, serving outside the building using a macro base station. Therefore, there is a continuity of service as a user
enters the building from outside, or leaves the building. This advantage is usually not available with the solutions of the small source in the building. Thus, in the case of Wi-Fi, Zigbee, etc., the wireless service from the same operator may not be available outdoors, requiring a reconnection as a user enters or leaves the building (The HetNet Forum, 2013).

3. Growing use of high frequencies in buildings and its impact
The tremendous growth in the data rate demand is causing the bandwidth requirement to increase by leaps and bounds. In order to cope with this requirement, wireless communication is gradually using higher and higher frequencies, as the lower frequency ranges are getting occupied. Although the cellular operation was defined for frequencies below 6 GHz up to 4 G, the 5 G cellular systems can encompass frequencies from 500 MHz to 100 GHz. The millimeter wave (mmWave), with a practical range from 10 GHz through 100 GHz, is a strong candidate for 5 G considering both outdoor and indoor uses (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016).

There are quite a few projects, to estimate and model the propagation environment for high frequencies, especially targeting 5 G, and a list of these major projects is shown in (Haneda et al., 2016). Previously, the outdoor-to-indoor propagation loss or building penetration loss (BPL) was measured and analyzed for frequencies only up to 10 GHz, and some of these works have been as cited in Okamoto et al., 2009. But recently, considering the new higher frequency requirements, measurements and analyses have been performed for frequencies up to 100 GHz. The authors of Zhao et al., 2013 present the measurement results of reflection and penetration at 28 GHz, for common building materials, such as brick, concrete, drywall, tinted glass, and clear glass. Outdoor materials, such as tinted glass and concrete were found to have high reflectivity and very low transmittivity. The penetration loss for outdoor tinted glass and indoor clear non-tinted glass was found to be 40.1 dB and 3.9 dB, respectively. Also, the indoor drywall revealed a penetration loss of 6.84 dB, whereas brick penetration through a pillar causes a much higher 28.3 dB loss. Thus, outdoor-to-indoor propagation can be quite difficult at 28 GHz, whereas indoor-to-indoor communication can be much easier.

Typical building facades are composed of several or composite materials, and the common materials are glass, concrete, metal, brick, wood, etc. Thus, the propagation of radio waves, into or out of a building, will in most cases be a combination of transmission paths, through different materials, through windows and through the facade between windows, allowing the signal deeper into the building, strongly dependent on the interior composition of the building. The authors of Haneda et al., 2016 show that different materials commonly used in building construction have very diverse penetration loss characteristics. Common glass tends to be relatively transparent with a rather weak increase in loss, with increasing frequency. Energy-efficient glass, commonly used in modern buildings, or in renovated buildings, is typically metal-coated for better thermal insulation. This coating introduces additional losses, which can be as high as 40 dB, even at lower frequencies. Materials, such as, concrete or brick, have losses that increase rapidly with frequency.

Other studies of the indoor coverage in the context of a single building scenario, with an outdoor-deployed base station, show that the building design factors, such as exterior wall material, interior layout, etc, are of crucial importance at high frequencies (Semaan et al., 2014). This study evaluated two building typologies, based on building wall configurations: old typology, having 30% standard glass windows and 70% concrete walls, and new typology, having 70% infrared reflective (IRR) glass windows and 30% concrete, as is common in modern energy-saving buildings. The simulation results of this study revealed that for new building types, providing outdoor to indoor coverage faces challenges at 30 GHz, and may get quite difficult at 60 GHz. While for the old building type, the penetration loss was found to be 6 dB at 1 GHz, 9 dB at 10 GHz and 19 dB at 100 GHz, for the new building type, the penetration loss was much greater; 14 dB at 1 GHz, 27 dB at 10 GHz, and 42 dB at 100 GHz. This shows a sharp increase in penetration losses with frequencies. It also shows that new building types, designed to achieve energy efficiency but
without considerations regarding wireless coverage, have much higher penetration losses than old building types, which may consequently pose problems for in-building coverage, assuming that signal from the outside base station is used. As more and more old buildings are being replaced by new ones, these results demonstrate the obvious need for architects to take these wireless coverage issues into consideration during design.

The authors of Ryan et al., 2017 present results from extensive measurements of penetration losses at 73 GHz, for various partition materials, in an indoor office, which were found significantly higher than the losses at 28 GHz (Zhao et al., 2013). For example, the indoor wall has a penetration loss of 10.6 dB at 73 GHz. Also, the authors of Cudak, 2016 present the measured penetration losses for various materials of hard and soft partitions at frequencies of 28 GHz, 39 GHz, and 73 GHz, and show that the penetration losses increase significantly with frequencies for almost all materials tested. Some exceptions include paver brick, cinder block, and foil faced-foam sheathing that have much higher penetration loss at 39 GHz than that at 73 GHz. The authors of Haneda et al., 2016 show that the following high frequency supported model represents BPL for buildings with typical low BPL and high BPL.

\[ BPL = 10 \log_{10}(A + Bf^2) \]  

(1)

Here, \( f \) is frequency in GHz, while \( A \) and \( B \) are constants depending on the condition of the building. The authors of Haneda et al., 2016 set \( A = 5 \) and \( B = 0.03 \) in order to fit the curve for the building with typical low BPL. Similarly, they set \( A = 10 \) and \( B = 5 \), to fit the curve for typical high BPL.

The majority of the measurement results, presented so far, uses the radio wave with perpendicular incidence to the external wall. The authors of Haneda et al., 2016 show that as the incidence angle becomes more grazing, the losses can increase by up to 15–20 dB. The surrounding environment of the building can also impose higher penetration losses at high frequencies. Compared to the losses in foliage at 2.8 GHz, the use of 28 GHz incurs an additional 3.3 dB loss for 2 m foliage and 8.6 dB for 10 m foliage, respectively.

It is thus evident that there is a good scope for architects, to work on the radio propagation environment in the building, and support RF engineers to encounter the growing challenge of operation at higher frequencies, especially using appropriate materials or combinations of materials.

4. Growing challenges of in-building wireless coverage

The global mobile data traffic is expected to increase from 19.01 exabytes per month in 2018 to 77.5 exabytes per month by 2022, at an annual growth rate of 46% (Clement, 2019). The dramatic growth is apparently nonstop and its technical support is going to be a great challenge, especially within built spaces. Technically, the data rate experience directly depends on the signal-to-interference plus noise ratio (SINR) at the receiver end. This is because higher SINR allows the use of a higher level of modulation and coding scheme (MCS), which directly increases the bit rate. Moreover, a data packet needs to be retransmitted if it is not correctly decoded at the receiving end. As SINR increases, the possibility of correct recovery of the packet increases, reducing the retransmission of packets. The carrier signal strength is typically the worst inside buildings because building materials cause propagation losses, which is a very contemporary concern, as people typically stay inside buildings most of the time in the present world.

Machine-to-Machine (M2M) communication is gradually causing many devices to be included in the wireless network. The BioT, an evolution of M2M communication, is expected to offer a wide array of applications in smart buildings with automated solutions for security, safety, energy management, comfort, entertainment, health, and so forth (Happiest Minds Technologies Pvt. Ltd., 2016). One will be able to control every aspect of the building, no matter where s/he is. The global market for BioT will continue to grow from 34.8 USDBn at the end of 2017 to 84.2 USDBn by
Besides, numerous new BIoT devices will potentially arrive in the future, and the idea about some of these devices is obscure at present.

In the course of time, the wireless service in buildings is occupying a more integral part of daily life, while the challenges to support the wireless service are also increasing with time for various reasons. A thorough analysis of these reasons has been made and it is presented below (Kawser, 2018).

1. **Data Rate Demand**: Both the number of wireless users and the data rate demand of an individual user are growing exponentially with time. The growth in the individual data rate demand is greatly affected by the introduction of high-quality video applications and online games. Moreover, the growth in the number of wireless devices, especially IoT devices, is colossal. Thus, the overall data rate demand is growing stupendously, which increases the challenge of wireless support.

2. **High Frequency Use**: The use of high frequencies, for 5G cellular communication, greatly increases propagation losses, and this makes the wireless coverage issue much more challenging. However, there is a fallacy that the radio signal can propagate further at higher frequencies. In fact, the radio signal dies out at a shorter distance, when the operating frequency is increased, because of the following reasons.
   
   (i) The free space path loss is smaller at lower frequencies. If the frequency is doubled, then the same free space path loss occurs at half a distance.
   
   (ii) Typically, higher frequencies greatly increase penetration losses. In general, the walls or other objects absorb more energy at higher frequencies, and so, the radio wave has more attenuation as it penetrates through obstacles.
   
   (iii) The lower frequency allows a higher angle of diffraction, and so, the radio wave can bend more around obstacles. As a result, the radio signal can reach more places, and the coverage holes can be minimized.
   
   (iv) When the radio wave is reflected by objects, higher energy is absorbed at higher frequencies. Thus, the reflected wave has a lower power at higher frequencies.

3. **Deep Locations of IoT Devices**: The wireless coverage requirement in the building, to support IoT devices, depends on various factors, for example,
   
   (i) the locations in the building where the devices are set up,
   
   (ii) the receiver sensitivity of the devices,
   
   (iii) the battery life of the devices,
   
   (iv) the maximum transmit power of the devices,
   
   (v) the antenna gain of the devices,
   
   (vi) the relative orientation between the device and the base station, and so forth.

In the worst case, the IoT devices can be set up deep into the building, and in places that are surrounded by various partitions. Both the building structure, and interior partitions can severely obstruct the signal, and then the propagation losses will be high. This challenge must be addressed in all possible ways due to the facts, shown below.

   (i) If the propagation losses are high, the large path loss can cause very low received power, and thus, it can be difficult or even impossible to operate the IoT devices.
   
   (ii) Most IoT devices in the building, for example, wireless sensors, are going to be not only wireless but also equipped with non-rechargeable batteries, potentially allowing easy setup and easy access within smart buildings (Mekkia et al., 2019). It will also be easy to retrofit a building with the new IoT devices in the future if they are wireless and battery operated. The battery replacement of these devices can be very inconvenient, or even practically
impossible. Thus, a key requirement, for these IoT devices, is a very large battery replacement period, preferably greater than 10 years (Takeda et al., 2016), often in sync with the device lifetime.

If the propagation losses are not low, the signal attenuation will be high. Then, the IoT devices will require high transmit power in uplink, to ensure sufficient signal strength at the receiver. This will cause the IoT device to drain out its battery quickly, which conflicts with the need for a very long battery life, mentioned above.

(4) Near-Far Problem for IBS: The near-far problem, a well-known RF issue, can arise very commonly in buildings when an IBS is used and there is sufficient signal level at the same frequency from the outside base station. Then, a user will suffer from significant interference. If the user is connected to an IBS, for example, DAS antennas, but the signal from the outside base station interferes significantly, the problem is referred to as an uplink near-far problem. On the other hand, when the user is connected to the outside base station and the signal from IBS interferes significantly, it is known as downlink near-far problem.

The macro base stations are carefully located at predesigned places, and they use careful frequency planning and interference management. Therefore, a macro user, typically, does not receive significant interference from neighboring base stations. However, proper planning may not always occur in the case of IBS. In the course of time, many new buildings may come up with the demand for IBS, and setting up IBS in all these buildings is not always well planned. Thus, due to the lack of proper planning, the IBS users may suffer from significant interference from the nearby macro base stations, leading to a significant near-far problem. The growth in the use of IBS can increase the near-far problem too.

(5) Spillage of Signals from IBS: In the case of IBS, the spillage of signals must be restricted to be less than −85 dBm on the street, and the adjacent buildings (Kulasekaran, 2015). It can often be difficult to maintain this requirement, especially, when an inadequate number of base stations are used, for picocells or femtocells, to cover a large building, thus requiring high transmit power from the base station. The growth in the use of IBS can increase the spillage of signals too.

(6) Potential Health Risks with 5 G: The health hazard is considered to be higher in the case of 5 G communication, compared to the existing wireless technologies, for two main reasons. Firstly, 5 G uses much higher frequencies, which may affect more adversely. Secondly, the high frequency signal in 5 G loses more power as it travels, especially through objects. This will require an increased density of base stations, and thus, people are likely to be exposed to higher RF radiation from a greater number of nearby base stations. Some research indicates that the use of 5 G communication may cause mutation of cells and induce tumors, and this can later lead to cancer. There may also be neurological effects, effects on skin or effects on eyes, from 5 G communication (David, 2019) (Verma et al., 2019).

The growing challenges to support wireless service in buildings need to be a major concern of the relevant authorities and experts right away. Although these challenges are more of the future than of now, these challenges need to be farsightedly considered now, as a building is usually not built just for a temporary period. The authors of Semaan et al., 2014 show that some contemporary building types, instead of assisting with the present demand, have increased penetration losses, compared to the old building types, thus, worsening the wireless coverage. This is partly due to the lack of awareness of architects, in this regard. Given the fact that the wireless coverage requirement can vary within the building, based on spatial and material issues, the architect can have significant ideas aiming to achieve these requirements, supplementing with much greater clarity to the understanding of RF engineers. Besides, specific locations in a building, where good coverage is essential, may be deprived or there can be coverage holes unless the architect consciously considers them.
5. Proposed guidelines for an architect’s role

This section proposes ideas about how an architect can contribute to improving wireless services and outlines the possible benefits therefrom. These proposals are primarily based on the authors’ interpretation of the information discussed so far while considering the engagement of architecture in the profession.

A. Proposed Guidelines

Considering the growing challenge of wireless support in buildings, the role of architects to address the challenges needs to be explored, in conjunction with the expertise of RF engineers’ guidance. By adjusting the radio propagation environment, they can help enhance the carrier signal, and attenuate the interfering signal. However, architects have not engaged in this concern so far, and through this paper, an attempt is being made to instill this concern into architects.

We propose that the architect, in the first step of the design process, determines, in collaboration with the RF engineer, which, among the three classes of wireless services, explained in Section II, would be used in the building. Then, the architect should design the building according to the requirements for the particular wireless service option chosen. Some guidelines are proposed below for the consideration of an architect in this regard. It should be noted that the purpose of this discussion is not to limit the proposed suggestions, rather to pave the way for research and generation of many new ideas.

(1) Using Low BPL for Outside Cellular Base Station: When the wireless service from outside cellular base station is selected for the building, we propose that the architect uses design and building materials, aiming to cause low outdoor-to-indoor building penetration loss. This low BPL will allow better signal entry from the outside base station. The architect can use various measures to implement low BPL. Some example measures are given below.

   (i) The architect can use large openings, voids, and windows towards the outside base station. Figure 1 shows such a building.

   (ii) The architect can use low penetration loss materials in the design, especially for the exterior surface. In windows or openings, one-layer ordinary glass can be used.

Figure 1. Building with low BPL for outside base station (Pinterest photos, 2019).
(iii) The architect should consider the landscape, and the surrounding environment of the building, especially because the penetration loss of foliage can be very high at high frequencies.

(2) Using High BPL for IBS: When the wireless service from an IBS is selected for a user in the building, we propose that the architect uses design and building materials, aiming to cause high outdoor-to-indoor building penetration loss, in order to block interference. This use of high BPL can help as follows.

(i) It can reduce the interfering signal, from the outside base station to a good extent, and mitigate the uplink near-far problem, explained in Section IV. The effectiveness of this proposed use of high BPL, in the mitigation of the uplink near-far problem, will be investigated in Section VI.

(ii) It can minimize the spillage of signals on the street, and on adjacent buildings, thereby controlling interference created from the building itself.

The architect can use various measures to implement high BPL. Some example measures are shown below.

(i) The architect can limit the number of openings. Figure 2 shows a building design that uses very few openings.

(ii) The architect can increase the use of high penetration loss materials, for example, concrete, in the design of the exterior facade.

(iii) In windows or openings, IRR glass can be used with two-layer glass or three-layer glass. This would have the added benefit of protecting the interior from heat.

(3) Open Planning: For any wireless service option, the use of open plan concept of architecture inside the building can allow many line of sight (LOS) links for the radio wave (Alfirevic & Alfirevic, 2016), and thus, can help signals propagate better and pervade throughout the building. For example, for WiGig, which uses both beamforming and very high frequency, the wireless coverage will be highly dependent on the uninterrupted paths within the building. It may be noted that the open plan can improve the received signal strength for both LOS and non-LOS wireless communication systems as the non-LOS path of radio signal is actually a composition of numerous LOS paths, as well as the effects of penetration, reflection, diffraction, and scattering (Kawser, 2018).
To improve the in-building coverage, we propose that the actual planning and design typology, inside the building, should be addressed, ensuring high pervasiveness of wireless signal, using the following methods.

(i) An open plan can be used in buildings, as shown in Figures 3 and 4. As the open plan attempts to avoid the use of real partitions, it allows the best propagation of the radio signal. The open plan concept is already getting popular, particularly in offices. With fewer walls to cut off the area, an open plan gives the appearance of more space, which is further compounded by the abundance of light. However, an open plan must attempt to fulfill the requirements of every individual, in terms of isolation or separation, control, quietness, etc., and these factors can be basically translated to privacy. The attempts may use privacy booths or privacy pods, freestanding conference pods, configurable benching workstations, low height partitions, mezzanine floors, and so forth. However, a perfect harmony or balance between privacy and collaboration, socialness, or optimal space utilization may often be very difficult in the building design (Commarch, 2019) (BHDP, 2019).

(ii) Voids, corridors, room size, and so forth can be incorporated to allow the geometry of space to enhance the openness in design. An example of this idea is shown in Figure 5.

(iii) Larger room size can be assigned for the given design brief when space is available.

(iv) Long, unobstructed corridors can be used, as shown in Figure 6.

(v) To improve the link between floors, vertical atriums or voids can be used as shown in Figures 7 and 8.

(4) Setting Hard and Soft Partitions: For any wireless service option, to improve the in-building coverage, we propose the careful design of both hard and soft partitions. An appropriate setting of hard and soft partitions can help allow the desired signal while blocking the interference signal. However, this requires proper knowledge and record, of the penetration loss for various building materials, and its variation with increasing frequencies. In this regard, we propose some guidelines below.

(i) The wall or partition materials can be chosen in order to maximize the desired signal power and minimize any interference signal power. Figure 9 shows the use of glass wall, along with the open plan, which can enhance the desired signal power.

(ii) Low height walls or partitions can be used towards the desired signal, and high walls or partitions can be used towards any interference signal.

(iii) Thin walls or partitions can be used towards the desired signal, and thick walls or partitions can be used towards any interference signal.
Figure 4. Use of open plan
(Luxus, 2019).

Figure 5. Openness created
inside the building (CSYA Architects, 2019).

Figure 6. Use of a long corridor
(STL Architects, 2019).

Figure 7. Section of a building
with vertical atrium (Chyutin Architects, 2019).
(iv) The position and orientation of hard or soft partitions can be carefully chosen depending on the position of user devices, the desired signal source, and the interfering signal source.

(v) Multiple reflective walls, fringes, or louvers may be used carefully to cause multipath signal bounce and to get to the receiver, as shown in Figure 10.

B. Outcome of Proposed Architect’s Contributions

The possible outcome of proposed the architect’s contribution can be manifold and it is summarized below.

(1) **Establishment of Wireless Coverage**: It can be much easier to improve the wireless coverage at the design phase, while the RF engineers will require less time, efforts, and cost.

(2) **Spectral Efficiency**: An improvement in the desired signal level, often accompanied by a reduction in the interference, can be possible, resulting in higher SINR. Thus, the available frequency spectrum or wireless resources, which are scarce, can be used more efficiently.
(3) **High Frequency Support**: The path loss of the signal can be much lower. Thus, it will be much easier to address the challenges of high frequency support and the high frequencies, with wider bandwidth availability, can be adopted for 5 G cellular and other technologies more readily.

(4) **Data Rate Experience**: The availability of higher SINR as well as larger bandwidth at high frequencies will culminate in much better data rate experience for the occupants of buildings.

(5) **Number of IoT Devices**: The overall data rate capacity can be significantly higher, allowing the building to be more easily equipped with a great number of IoT devices, and this will be a requirement of smart buildings in the future.

(6) **Coverage in Specific Locations**: The specific locations in a building, where good wireless coverage is essential, as the architect is aware of, can be given proper care, ensuring sufficient signal level.

(7) **IoT Devices at Deeper Locations**: Because of improved wireless coverage, the IoT devices, at deeper locations in buildings, can be operable with greater efficiency.

(8) **Battery Lives of IoT Devices**: Because of reduced path loss for the signal, the IoT devices will require less transmit power in uplink. This will save battery power meeting the requirement of a very long lifetime of the IoT devices.

(9) **Spillage of Signal**: The undesired spillage of signal outside the building can be mitigated.

(10) **Health Hazard with 5 G**: Because of reduced path loss for the signal, the required transmit power, whether the source of transmission is located outside or inside the building, can be less. Thus, the health hazards, from electromagnetic radiation with 5 G cellular technology, can be mitigated.

It is thus evident that in the course of time, the architectural interventions, suggested in this paper, will find their impact more and more meaningful. Since the benefits of the proposed contributions from architects are conspicuous, considering the future requirements, these contributions may be justified in many cases and sometimes, even at the cost of slightly degrading aesthetic appeal or other present architectural concerns.
6. Performance analysis of proposed solution to uplink near-far problem

When a user is served by an IBS and there is a significant level of signal at the same frequency from the outside base station, the uplink near-far problem can significantly affect the data rate experience of a user in a building, as explained in Section IV. An architectural solution, proposed in Section V, can be an effective remedy to this problem. In this section, the improvement in data rate experience, from the proposed architectural solution, will be investigated using simulation. For this purpose, it is assumed that there is a user and an IBS inside a building, and that there is a macro base station outside the building. The IBS and the macro base station use the same frequency. The user device receives the desired signal from the IBS, and it also receives interference from the macro base station, leading to the uplink near-far problem. The scenario is simulated with two conditions. In the first case, the performance of wireless usage is not taken into account at the design phase and the building uses low BPL. In the second case, according to the proposed solution, the architect consciously uses high BPL in the building, attempting to mitigate the uplink near-far problem. The performance of the two cases is compared.

Considering the promises of 5G for the future, the investigation will assume 5G operation. Although 5G supports both low and high ranges of frequencies, in the distant future, the use of high frequencies is expected to outweigh the use of low frequencies. The three bands, located at 28 GHz, 38 GHz, and 73 GHz, are already the most popular choices for 5G deployment (National Instruments, 2019). Besides, limited investigations have been performed at high frequencies so far. Therefore, only the high range of frequencies is considered in this section. The simulation uses nine equidistant frequency values from 10 GHz through 90 GHz.

It is assumed that $S_{IBS}$ represents the power received from the IBS, $I_{Macro}$ represents the interference power received from the macro base station, $N_0$ is the white noise power spectral density, and $\Delta f$ refers to the bandwidth used. In this case, the downlink SINR for the user equipment (UE) can be expressed by (Lee et al., 2010)

$$\text{SINR} = \frac{S_{IBS}}{N_0\Delta f + I_{Macro}}$$

(2)

The data rate of a user depends on SINR, the used frequency range $\Delta f$, the technology used in the data transfer, and the allowed or target bit error rate (BER). The BER represents the number of bits in error, divided by the total number of transferred bits. The practical data rate of a user in bits/sec can be given by (Lee et al., 2010)

$$R = \Delta f \log_2 (1 + \alpha \text{SINR})$$

(3)

where $\alpha$ is a constant for target BER and defined by $\alpha = 1.5/\log_e(5)$ (5. BER). Here, the target BER is set to $10^{-6}$ (Lee et al., 2010).

$S_{IBS}$ and $I_{Macro}$ are the amount of received power in (2). The power received from a source can be computed as $P.G$ where $P$ represents the transmit power, and $G$ represents the channel gain.

The path loss is the amount of reduction in power, of an electromagnetic wave as it propagates through space. Ignoring the small-scale fading and shadowing effects, the relationship between the channel gain $G$ and path loss $PL$ can be shown as (Lee et al., 2010)

$$G = 10^{-PL/10}.$$  

(4)

Because of the assumption of 5G systems, a path loss model, supporting frequencies up to 100 GHz, needs to be used to estimate $PL$. The Alpha-Beta-Gamma (ABG) is popular among such path loss models and so, it is selected here. The ABG model can be applied from 500 MHz through 100 GHz, and its parameters are invariant to the operating frequency (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016).
For outdoor scenarios, the path loss in the ABG model is given in dB as (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016)

\[ PL_{\text{outdoor}} = 10\alpha \log_{10}(d) + \beta + 10\gamma \log_{10}(f) + X_{ABG}^{\sigma} \quad (5) \]

For the indoor scenarios, the dual-slope ABG model can be used to determine the path loss. Here, the path loss is given in dB as

\[ PL_{\text{indoor}} = \begin{cases} 
10\alpha_1 \log_{10}(d) + \beta_1 + 10\gamma \log_{10}(f) & 1 < d < d_{BP}^1 \\
10\alpha_2 \log_{10}(d_{BP}) + \beta_1 + 10\gamma \log_{10}(f) + 10\alpha_2 \log_{10}\left(\frac{d}{d_{BP}}\right) & d > d_{BP}.
\end{cases} \quad (6) \]

Here, \( d \) represents the distance between the transmitter and the receiver in meters, \( \alpha \) captures how the path loss increases with \( d \), \( \beta \) is a floating offset value in dB, \( \gamma \) captures the path loss variation over the frequency \( f \) in GHz, and \( X_{ABG}^{\sigma} \) captures the shadow fading in dB (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016).

When the signal reaches inside the building from the outside base station, it encounters additional signal attenuation due to outdoor-to-indoor building penetration loss (BPL). As shown in (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016), the total path loss will then be approximately

\[ PL_{\text{total}} = PL_{\text{outdoor}} + BPL \quad (7) \]

ignoring the loss due to the location of the receiver, away from the exterior wall of the building. The BPL for buildings with typical low BPL and high BPL can be determined using (1) with the constant values shown in Section III.

\( S_{\text{IBS}} \) can be determined using the transmit power of IBS, shown in Table 1 and the indoor channel gain. Here, the channel gain needs to be determined by first calculating the path loss \( PL_{\text{indoor}} \) according to (6) and then using (4). In this case, the distance between user and IBS is shown in Table 1. Similarly, \( I_{\text{Macro}} \) can be determined, using the transmit power of macro base station and the channel gain. Here, the channel gain needs to be determined by first calculating the path loss

| Table 1. Simulation assumptions |
|---------------------------------|
| **Parameter**                   | **Value**                                   |
| Transmit power of macro base station | 4.3 dBm (3GPP TR 36.814, 2017)             |
| Transmit power of IBS            | 20 dBm (3GPP TR 36.814, 2017)              |
| Distance between user and IBS    | 10 m                                        |
| Distance between user and macro base station | 40, 60, 80 m                              |
| Channel bandwidth                | 10 MHz (3GPP TR 36.814, 2017)              |
| Carrier frequency                | 10 - 90 GHz                                 |
| Constants for ABG model (outdoor case) | \( \alpha = 3.4, \beta = 19.2, \gamma = 2.3 \text{ and } X_{ABG}^{\sigma} = 6.5 \) (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016) |
| Constants for dual-slope ABG model (indoor case) | \( \alpha_1 = 1.7, \alpha_2 = 4.17, \beta_1 = 33, \gamma = 2.49 \text{ and } d_{BP} = 6.9 \text{ m} \) (Aalto University, Nokia, NTT DOCOMO, Ericsson Qualcomm, Huawei, Samsung, INTEL, University of Southern California, 2016) |
| Constants for building with high BPL | \( A = 10 \text{ and } B = 5 \) (Haneda et al., 2016) |
| Constants for building with low BPL | \( A = 5 \text{ and } B = 0.03 \) (Haneda et al., 2016) |
| Target Bit Error Rate (BER)      | \( 10^{-6} \) (Lee et al., 2010)           |
| White noise power density, \( N_0 \) (Thermal noise floor at room temperature, 300° K) | \(-174 \text{ dBm/Hz} \) (3GPP TR 36.931, 2018) |
To determine $P_{L_{\text{total}}}$, $P_{L_{\text{outdoor}}}$ is calculated using (5) for three different distances shown in Table 1, and BPL is calculated using (1). Then, $P_{L_{\text{total}}}$ can be calculated using (7). Finally, SINR can be determined using (2) and the user data rate can be determined using (3). The user data rate is used as an indicator of the user experience.

For the purpose of the above computation, a MATLAB code was developed. The simulation results compare the performance of the two cases, the use of low BPL and high BPL, in terms of their user data rates. The simulation was performed for three different distances between the user and the macro base station, 40 m, 60 m, and 80 m, and the simulation results are shown for these distances in Figures 11-13, respectively. The simulation assumptions are shown in Table 1.

The simulation results, presented in Figures 11-13, demonstrate that the user data rate can improve significantly with the proposed use of high BPL as an architectural solution. However, at very high frequencies (above 60 GHz), the improvement of the proposed solution is found to decline gradually. The improvement in data rate is found more pronounced for a shorter distance between the user and the macro base station. This is primarily because at a shorter distance, the interference from the macro base station is more prominent, and so, a protection against the interference is also of greater help. The ABG models, for both outdoor and indoor cases, have large and non-linear dependencies on frequencies. Also, (1) gives a parabolic relationship of the penetration losses with frequencies. Consequently, the variation of the data rate is found wide but irregular with frequencies.

Figure 11. Data rate (Mbps) vs. frequency (GHz) for the outside base station 40 m away.

Figure 12. Data rate (Mbps) vs. frequency (GHz) for the outside base station 60 m away.
7. Conclusion
A growing interdisciplinary concern has been addressed, in this paper, regarding a new paradigm that is being posed by wireless technology, a hallmark of the modern era, in the design of built spaces. While it is clear that the domain is currently addressed by RF engineers, the actual design of spaces is left to architects, who are not enough conversant with the various nuances of wireless coverage. In this paper, analyses have been presented to spur an architect to contribute to the improvement of in-building wireless coverage and real farsightedness can clarify its necessity. Some guidelines are proposed for the contribution of architects. This is expected to pave the way for further research in this arena.

The paper ends by investigating one of the proposed architectural solutions, addressing the near-far problem in buildings. The results demonstrate significant improvement in data rate experience when the proposal is used. Finally, it can be highlighted that the contributions from architects, in collaboration with RF engineers, to achieve efficient wireless connectivity, cannot be left as an afterthought. Adequate design input at the early stages is understated, and proper attention from the design stage will ensure, as explained in this paper, various conspicuous benefits.

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