Advanced radio over fiber network technologies

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Abstract: The evolution of wireless communication networks supporting emerging broadband services and applications offers new opportunities for realizing integrated optical and wireless network infrastructures. We report on some of our recent activities investigating advanced technologies for next generation converged optical wireless networks. Developments in Active Antenna Systems, mobile fronthaul architectures, and 60 GHz fiber distributed wireless networks are described. We also discuss the potential for analog radio over fiber distribution links as a viable solution for meeting the capacity requirements of new network architectures.

OCIS codes: (060.2360) Fiber optics links and subsystems; (060.5625) Radio frequency photonics.

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1. Introduction

The convergence of optical and wireless networks continues to evolve, ever since the first reports of using optical fiber as feeder links to extend wireless coverage that were published more than two decades ago [1,2]. The benefits of creating integrated end-to-end network

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solutions that can provide reliable service for both fixed and mobile users is now well-recognized.

Today the capabilities of wireless networks are progressing more rapidly than ever before. The proliferation of connected high capacity devices such as tablets and smart phones as well as the increase in the number of broadband multi-media services available to the consumer has led to an unprecedented demand for wireless access to high-speed data communications. Optical fiber links are also increasingly being used to provide the backhaul connections for these high capacity mobile networks. The realization of integrated optical/wireless networks that can reliably and cost-effectively support current and future capacity demands, traffic growth rates, new services, as well as multiple wireless standards, presents new challenges.

In this paper we report on some of our recent activities investigating advanced technologies for next generation converged optical wireless network infrastructures. We also discuss some of the tradeoffs associated with the candidate radio signal transmission technologies for emerging high data rate mobile fronthaul applications.

2. Active Antenna Systems (AAS)

Both analog and digital photonic links can be used to transport radio signals over optical fiber; each transmission technique has certain tradeoffs. Digital fiber optic links are typically used in today's traditional macro-cellular communication networks which feature a distributed base station architecture in which the radio hardware is positioned in close proximity to the tower-mounted passive antennas. This remote radio head (RRH) contains the RF circuitry as well as the analog-to-digital/digital-to-analog converters and frequency conversion components. Meanwhile the base station server (BTS) or baseband unit (BBU) comprising the digital baseband processing circuitry is located separately and interfaces with the RRH via a digital fiber optic link; CPRI (Common Public Radio Interface) and OBSAI (Open Base Station Architecture Initiative) are two standards that have been developed for this serial link.

One emerging architecture concept attracting significant interest for meeting the growing capacity and traffic demands of wireless networks is the selective deployment of smaller sized cells that would coexist with, and complement larger macro-cells. As part of this trend, the cell site hardware is also becoming more advanced. Active antenna systems (AASs) are key examples of this technology innovation; an extension of the distributed base station concept in which the RRH functionality is now directly integrated with the antenna elements [3]. The active antenna is also becoming more 'intelligent' since its radiation patterns can be adapted to accommodate changing capacity demands and even multiple wireless standards in the one cell. Recent network trials have demonstrated the energy efficiency improvements and base station performance benefits (capacity, coverage) of AAS technology [4–6].

New antenna array structures capable of supporting a variety of wireless standards and able to accommodate the next generation form factors of radio cell sites will play a key role in wireless base stations featuring AAS. In addition to being able to operate efficiently over the entire frequency spectrum, the arrays must feature beam steering capability over a wide field of view with a small factor; the combination of these requirements presents a significant design challenge for realizing the AAS arrays.

One promising radiator candidate for implementation in next generation multi-radio AAS is the balanced anti-podal Vivaldi antenna (BAVA) structure [7]. These antenna elements are inherently wideband in nature, electrically small and also modular, allowing easy formation into an array. The BAVA does not encounter the typical scan blindness and grating lobe issues associated with creating large arrays of wideband antenna elements, which leads to a very efficient radiating system. It is also very suited to being integrated with component technologies for small cell applications.

Figure 1(a) shows an array of wideband BAVA elements in a highly compact single platform that we recently investigated for a multi-standard (2G, 3G and LTE) active antenna system [8]. The array was designed to efficiently cover the 700 – 3600 MHz frequency range with good beam steering capabilities over multiple octaves, as highlighted in the VSWR (Voltage Standing Wave Ratio) and radiation pattern plots of Figs. 1(b) and 1(c), respectively.

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New multi-service AASs will require linear two dimensional (2D) and possibly even 3D beamforming techniques. Although MIMO (Multiple Input Multiple Output)/spatial multiplexing systems have been successful in yielding higher throughput in present day systems, the increase in capacity is still not sufficient for emerging systems.

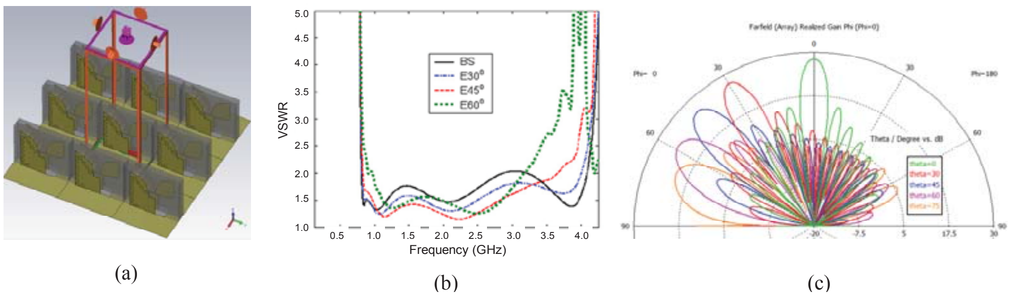

Fig. 1. BAVA array developed for next generation active antenna *s*ystem. (a) Schematic. (b) Voltage Standing Wave Ratio (VSWR) for several scan angles. (c) Radiation patterns.

3. Integration with optical networks

Alongside the move towards smaller cell sites with integrated antennas and RRH functionality, the interconnections between the active antenna systems and the baseband units are also evolving. In the traditional arrangement the BBU is located in a cabinet at the base of the cell tower however the concept of a centralized architecture in which a number of BBUs are remotely co-located together in a secure Central Office, as depicted in Fig. 2, is being actively pursued [9,10]. In this scenario, the typical digital fiber-optic link between the AAS or RRH and the BBU would be longer in length and the optical distribution network comprising the digital links constitutes the fronthaul of the wireless network.

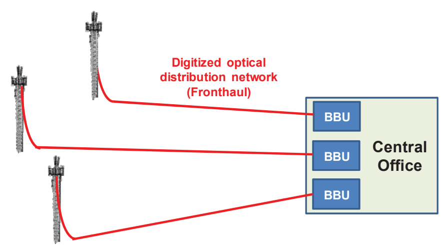

Fig. 2. Schematic showing the concept of a centralized BBU architecture for future integrated optical wireless networks

A centralized BBU architecture such as that shown above, is expected to lead to savings in OPEX (Operating Expenditure) as well as improved performance since there is no transmission delay between adjacent cells. If the co-located BBUs are also pooled together such that the baseband processing resources can be effectively shared across a large number of cell sites in a "virtual" configuration, the resulting cloud radio access network (C-RAN) can also enable CAPEX (Capital Expenditure) reductions while enabling the connectivity between different wireless network layers to be optimized. One of the key challenges associated with remoting pooled BBUs from the active antenna systems in next generation wireless networks is the very high bit-rates that must be accommodated by the digital links since the data rate will depend on the sampling frequency (proportional to the wireless data bandwidth) and sampling resolution [11]. This problem becomes more pronounced with the trend towards using multiple transmit and receive antennas at the cell site as a means to increase capacity. For example, an LTE network with 20 MHz bandwidth, 2 × 2 MIMO in the downlink, and 3 sectors (RRHs) per cell site would equate to an aggregate data rate of more than 7 Gb/s after digital sampling of the analog radio signals [10]. The implementation of

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AASs with multiple radios that support a diversity of wireless standards can lead to expected data rates well in excess of tens of Gb/s over the next few years. In addition, there are strict requirements on transmission latency and jitter that must be satisfied, which are even more stringent for emerging higher data rate 4G wireless networks. Ultimately these constraints will limit the fiber distances between the active antenna systems and the baseband processing hardware to a few tens of kilometers.

One approach to addressing the challenge of realizing high data rate fiber optic links for future wireless fronthaul networks is the development of novel digital compression algorithms to reduce the bandwidth [9]. A complete paradigm shift however would be to consider analog RF-over-fiber optical links which would avoid the digitization process altogether [8,12]. By removing the need for sampling, an analog optical distribution network connecting the AASs and BBUs could more easily support future wireless networks offering multiple broadband services by exploiting readily available lower bandwidth optical transceivers. It would also greatly simplify the cell site hardware and reduce power consumption since the ADC/DACs and frequency up/-downconversion circuitry are no longer required.

A significant drawback with transporting wireless signals as an analog signal over fiber is the reduced dynamic range which limits the fiber transmission distance. This is highlighted in Fig. 3 which compares the dynamic range performance of an analog and digital optical link as a function of link length [11]. This RF-over-fiber transmission scheme is also subject to the impact of nonlinearities associated with the photonic and electronic devices in the link [13]. A variety of linearization schemes suitable for correction of analog photonic link nonlinearities have been reported in the literature including predistortion [14] and feedforward [15] architectures. An analog based connection would also have an impact on feasible architecture options for the optical distribution network that interfaces multiple small cell sites to a centralized pool of BBUs since this signal transport scheme is not compatible with TDM PONs (Time Division Multiplexing Passive Optical Networks).

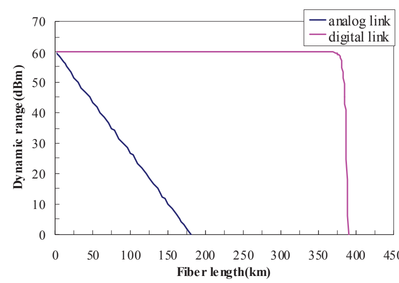

Fig. 3. Comparison of dynamic range versus fiber transmission distance for analog and digital optical links

4. 60 GHz small cells

The unlicensed and globally available 60 GHz frequency region for wireless communications is currently attracting much interest worldwide because of the huge bandwidth it can provide. The 7 – 8 GHz of bandwidth available between 57 and 66 GHz enables multi-Gb/s data rates to be supported for a diversity of applications. A 60 GHz WPAN (Wireless Personal Area Network) is a type of small cell featuring lower transmission power and reduced coverage area that has the potential to meet the growing capacity demands of wireless networks. Integrating a 60 GHz small cell with a fiber-optic distribution network would allow the efficient delivery of the high data rate signals to a large number of RRHs ensuring optimized radio coverage [16,17].

The fiber remoted RRH of a 60 GHz small cell requires an efficient radiating solution where the antenna is capable of providing both high gain as well as the typical radiation pattern required in a cellular infrastructure. The radiator structure such as that shown in Fig. 4 has the potential to satisfy both requirements [9]. In this approach, we utilize a printed

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antenna lens configuration due to its low feed loss, ease of construction and overall small form factor, to achieve high gain. Our novel radiating structure incorporates a feed array of printed antennas with an extended hemispherical lens to achieve the appropriate radiation pattern, with the dielectric layers used to create the antenna optimized to ensure maximum radiation efficiency.

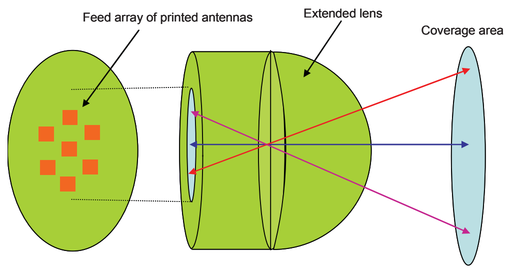
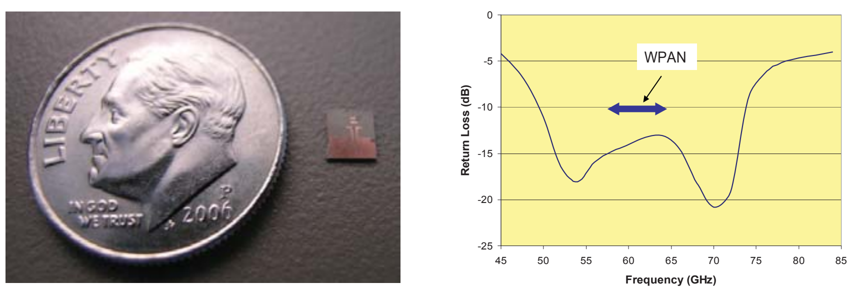


Fig. 4. Multiple beam lens based radiator structure created for 60 GHz small cells

The lens excitation radiator developed for the 60 GHz RRH antenna was a uni-planar quasi-Yagi printed antenna, shown in Fig. 5(a). Here all the conductors, including the reflector element, were developed on a single layer and no broadband balun was used. The measured reflection coefficient of the quasi-Yagi printed antenna is shown in Fig. 5(b). Good return loss performance was achieved over a wide bandwidth, from 57 to 64 GHz, using this novel structure. The gain of the single printed antenna was around 4 dBi.

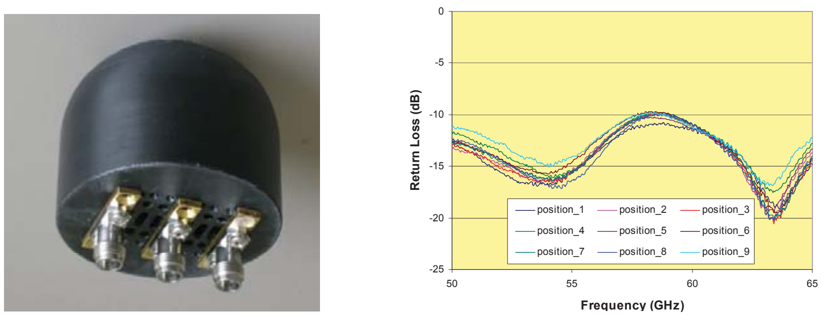


(a) (b)

Fig. 5. (a) Photograph and (b) Measured reflection coefficient of the developed uni-planar quasi-Yagi 60 GHz printed antenna

Figure 6(a) shows a photograph of the 60 GHz multiple beam lens antenna that we developed based on the concept depicted in Fig. 4. The extended hemispherical lens was made from polyethelyne; the radius of the hemispherical part of the lens was 25 mm and the extension was 17 mm. We expected this combination should yield a maximum gain of approximately 20 dBi. To accommodate multiple quasi-Yagi antennas within the lens, slots were formed in the material. The extension of the lens was increased by 5.3 mm to allow for the quasi Yagi antennas to reside within the lens. A total of nine slots were cut at a spacing of 3.5 mm to allow for wide beam coverage and minimal gain undulation between the beams.

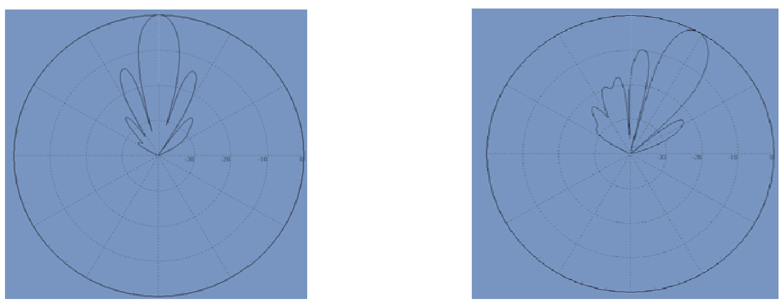
The photograph in Fig. 6(a) shows the lens with three quasi-Yagi antennas located in several of the slot positions. The measured return loss of the developed 60 GHz multiple beam lens antenna with the quasi-Yagi feed antenna located in different slot positions in shown in Fig. 6(b). This graph shows the return loss of the lens antenna when the quasi-Yagi radiator is located in all nine slot positions; the center position is labeled as number 5. As can be seen from this plot the multiple beam lens antenna meets the bandwidth requirements for a 60 GHz small cell and any change in impedance as the feed position is varied is small. The slight variation observed is due to the elements seeing a slightly different surrounding as the location of the quasi-Yagi antenna is shifted.



(a) (b)

Fig. 6. (a) Photograph and (b) Measured reflection coefficient for different excitation element positions of the developed multiple beam 60 GHz lens antenna

Figure 7 shows several examples of the radiation patterns of the 60 GHz multiple beam lens antenna in the upper hemisphere when the quasi-Yagi feed antenna is located in different slot positions; Figs. 7(a) and 7(b) correspond to the fifth and the seventh slot positions, respectively. These plots highlight the multi-beam nature of the 60 GHz antenna and its usefulness for a fiber distributed 60 GHz RRH.



(a) (b)

Fig. 7. Examples of radiation patterns of the 60 GHz multiple beam lens antenna; (a) Slot position 5 and (b) Slot position 7

7. Conclusions

Meeting current and future capacity demands and supporting multiple wireless standards continue to drive the evolution of wireless networks. Active antenna systems, centralized BBU architectures, Cloud Radio Access Networks, and 60 GHz small cells are some of the emerging concepts being explored for these next generation wireless systems, which have the potential to significantly impact the evolution of converged optical and wireless networks. A key challenge in successfully realizing the optical distribution network for future wireless fronthaul will be the very large bit rates per cell site that must be supported. Analog optical distribution networks may offer a viable alternative to conventional digital fiber optic links between the RRH and BBU for next generation integrated networks.

We have also described the development of a new type of antenna structure that may be suitable for future fiber distributed 60 GHz small cells supporting large data transmission rates. The antenna can satisfy both bandwidth and coverage requirements in a small form factor.