Augmented-Reality Optical Narrowcasting (ARON)

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Abstract—**We introduce a new communications technology for consumers in Smart Cities, which we refer to as Augmented-Reality Optical Narrowcasting (ARON). This technology has the potential to significantly enhance mobile consumer communications by enabling information exchange between multiple transmitters and multiple receivers using free-space optical data transmission in the near infrared. A practical communication range of 400 meters in broad daylight is achievable with miniaturized optics transmitting HD video, for example, to smartphones and 1,000 meters to vehicles. An augmented-reality-style user interface, wherein visual representations of available information sources are overlaid on a live display of local video imagery allows users to conveniently manage transmissions from multiple parties. The new technology is envisioned to be installed in smartphones and other mobile devices and in vehicles, opening new vistas for commerce and social interaction. We have demonstrated key features of the technology using custom optical communications hardware and software developed especially for this purpose.**

Keywords- optical communication; augmented reality; smartphones; automobiles; nonimaging optics.

I. INTRODUCTION

In 1880, Alexander Graham Bell patented and demonstrated the world's first free space optical communication system, which he dubbed the Photophone. Bell achieved the first ever over-the-air voice transmission over a distance of 213 meters using meter-sized transmitter and receiver parabolic mirror dishes harnessing modulated sunlight. This achievement preceded by 19 years the first demonstration of radio by Marconi [1]. In his latter years, Bell stated that he believed this invention was "…greater than the telephone" [1].

In modern times, there have been several attempts, largely unsuccessful, to commercialize this technology. The Maxima Corporation published its operating theory in Science [2], and received $9 million in funding before permanently shutting down. No known spin-off or purchase followed this effort. In 2004, a Visible Light Communication Consortium was formed in Japan [3]. This was based on work from researchers that used a white Light Emitting Diode (LED)-based space lighting system for indoor Local Area Network (LAN) communications. Projected data rates and future data rate claims vary - a low-cost white LED (GaN-phosphor) which could be used for space lighting can typically be modulated up to 20 MHz [4]. Research published in 2009 used a system for traffic control of automated vehicles with LED traffic lights [5]. Increased security when working with narrow beams has also been demonstrated [6].

Our approach is conceptually and technically different from all previous commercialization attempts. We introduce a new type of communications channel, intended for the consumer in a Smart Cities environment. We refer to this technology as Augmented-Reality Optical Narrowcasting (ARON). ARON is a pioneering communications technology that transmits information locally using LED-generated beams of near-infrared light with tailored directionality. ARON offers a robust many-transmitters to many-receivers free-space optical communications channel for personal use with mobile devices (such as smartphones and automobiles). We envision the use of this localized optical communications channel as a means to enhance information flow, free-up overtaxed Radio Frequency (RF) bands, create a new class of mobile social networks, and provide a novel user experience.

In Section II, we discuss how the physics of optical communication differ from radio communication and how we can exploit these differences. In Section III, we discuss the underlying principles of our ARON architecture and how they significantly differ from prior work. In Section IV, we discuss the architecture of a new type of optical information processing chip, the Adaptive Communications Focal Plane Array (ACFPA), and how that design folds into our concept. In Section V, we present the assumptions and physics model for our signal to noise tradeoffs. In Section VI, we discuss our Technology Demonstration Unit (TDU) and real-life test results. In Section VII, we present conclusions and offer comments about how ARON can impact Smart Cities.

II. THE PHYSICS OF ELECTROMAGNETIC WAVE TRANSMISSION AND RECEPTION

RF waves are electromagnetic (EM) waves of frequency between 3 hertz (Hz) and 300 gigahertz (GHz). These waves readily reflect, refract and diffract. Due to their long wavelengths, radio waves can navigate around obstacles and also penetrate some types of materials. This is much less true of light waves which, due to their short wavelengths, require a line of sight to achieve a viable communications path and cannot penetrate most materials. These seeming limitations of light waves have until now stalled the development of free-space optical communications for use by the consumer - possibly because it was always considered an impractical proposition. Consequently, the only free-space optical device that has ever really achieved commercial success is the celebrated TV remote control.

EM waves propagating through the atmosphere obey the non-interference principle (i.e., EM waves originating from multiple transmitters do not exert force on each other). So, waves from multiple sources pass through each other unaffected. This occurs because Maxwell's equations are linear in the electric and magnetic fields, and in their sources, so the superposition of two solutions is also a solution. This is true of EM waves in both the RF band and the optical frequency band, but there is a major difference between the two types of waves which has to do with the physics of the intended receiver. Oscillating EM waves used in radio transmissions are designed to be detected via their interaction with a conducting antenna, in which an Alternating Current (AC) is induced with a frequency equal to that of the carrier EM wave. Consequently, if two EM waves utilizing the same carrier frequency and comparable strengths are transmitted in proximity to each other, the induced AC currents on the conducting antenna will superimpose and jamming will occur. This issue, associated with the detection of radio waves, has far reaching consequences requiring the strict allocation of broadcast transmission frequencies to different parties.

The authority for controlling the use of RF frequencies in the United States resides with the Federal Communications Commission (FCC). The FCC also regulates content and requires broadcasters (government, corporate and amateur) to be licensed. The RF spectrum, the total range of radio frequencies that can be used for communication in a given area, is a limited resource. Each radio transmission occupies a portion of the total bandwidth available. RF bandwidth is regarded as an economic commodity, which has a high monetary cost and is in increasing demand. Because it is a fixed resource which is in demand by an increasing number of users, the RF spectrum has become increasingly congested in recent decades, and the need to use it more effectively is driving many additional radio innovations, such as trunked radio systems, spread spectrum (ultra-wideband) transmission, frequency reuse, dynamic spectrum management, frequency pooling, and cognitive radio. The FCC, however, has no jurisdiction over the use of light waves for communication.

Light waves are also a form of EM waves but they differ from RF in one important aspect: because light photons are on the order of a million times more energetic than their RF counterparts, then instead of a conducting antenna, a different mechanism is employed for their reception. A carrier wave for optical transmission is not necessary (to induce an AC current on an antenna) and the receiver comprises a focal plane array of miniature photodiodes. High energy photons impacting the receiver focal plane detector array cause electrons to be emitted. This is a highly localized phenomenon (with low spatial crossover noise). Consequently, a focal plane array may receive (and process) multiple signals simultaneously without experiencing jamming or interference, as long as there is some spatial separation between the respective receiving array detectors. This mechanism offers us an opportunity to implement a novel receiver strategy of angular multiplexing which we can exploit to remediate the problem of potential obstructions to the optical transmission line of sight. In essence, our method will be to employ a redundant transmission of identical optical signals, narrowcast at the same frequency, containing the same identical data stream, but transmitted from spatially distinct origins.

Optical data transmission has no spectrum regulations attached to it. Additional loads to the RF spectrum introduced by Smart Cities, the Internet of Things, and now, the ubiquitous use of RF communications for the most mundane of tasks are already taxing the availability of clear channels in that spectrum. Unregulated optical alternatives are a simple way to relieve some of this stress and reduce the data collisions that will become more and more common in the future.

Some of the benefits of employing a free-space optical communication system vs RF are:

- Alternative optical many-to-many localized communications channel
- Independent of cell phone data plans or the Internet
- Unregulated, uncensored and free to use
- Capable of forming localized social networks between individuals/vehicles within visual range without login
- Receive educational and entertainment information in theme parks, museums and conferences
- Receive information from virtually generated electronic billboards both indoors (e.g., airports) or outdoors
- Universal international use without limitation or data plan
- Stress reduction for the already overtaxed RF spectrum
- Energy-efficient, low power
- Does not require geolocation
- Highly secure (if so desired) because optical data beams do not have leaking sidelobes

III. THE PRINCIPLES OF AUGMENTED-REALITY OPTICAL NARROWCASTING (ARON)

The augmented reality aspect of ARON (US Patent 9,747,503 [7]) provides the user with data overlaid over the field of view of the human eye, supplementing the experience of natural vision with information. Narrowcasting is distinguished from broadcasting in that the transmitted radiation field containing the optical signal is limited in range and in its projected solid angle.

ARON provides a user experience like no other. The receiver (e.g., an ARON-equipped smartphone) is held vertically and the user views their surroundings through the wide angle camera function of a smartphone. ARON transmitters are similar to small inexpensive flashlights, can be installed outdoors and their data content is programmable. Since ARON does not require a cell plan, WiFi, Bluetooth or any kind of network login the usage is very simple and natural, and is intended to enhance the normal human vision experience.

ARON provides a many (transmitters) to many (receivers) network topology. ARON eliminates the need for the precise alignment of optical transmitters and receivers, due to its configurable narrowcast and wide receive angles, making optical communications at ranges of hundreds of meters practical and convenient for handheld use with mobile devices. Data received optically is automatically integrated with imagery from mobile-device cameras, thereby providing a user-friendly AR experience without the need for complex AR software and inputs from additional sensors.

To prevent obstruction of the line-of-sight optical signals and ensure robustness of use we implement a 3-step mitigation process:

1) We employ a robust forward error correction algorithm (i.e. data and retrieval buffering) of the signal which compensates for short term obstructions (Fig. 1).

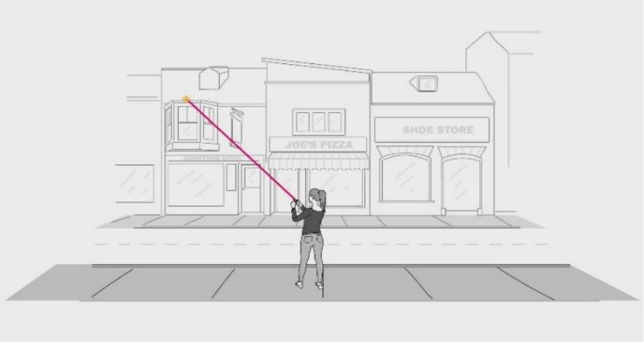

Figure 1. Forward error correction algorithm compensates for temporary obstructions.

2) We expand the emission beam from a pencil-like beam to a uniform, configurable, broad beam using nonimaging optics [8] so that the receiver does not need to be accurately aligned with the beam (Fig. 2) and multiple users can receive the data from any transmitter.

3) We employ multiple emitters, which through spatial separation, and angular multiplexing at the receiver's focal plane array, coupled with an AI-style adaptive processing algorithm achieve a photonic cross-fire mode, ensuring with very high probability that at least one of the transmissions of interest will always reach the receiver (Fig. 3).

Figure 2. Expanding the transmitter beam into a uniform swath.

Figure 3. Combining transmitter swaths to achieve photonic cross-fire and a many-to-many network topology.

ARON provides a secure optical communication channel with capabilities that complement, rather than replace, Wi-Fi and other RF technologies. Our patented Adaptive Communications Focal-Plane Array can also function as an ultra-high-data-rate replacement for conventional RF-based Wi-Fi systems and can also be used for Li-Fi communications.

As an optical, rather than RF, communication channel, ARON is not subject to regulation by the FCC. Its directional, localized characteristics provide a unique capability to securely send and receive information in a manner that is difficult to achieve using RF channels, such as interacting with mobile emitters. ARON provides a natural, user-friendly method of exploring a local environment (e.g., a shopping district) using an intuitive, visually-oriented AR interface (Fig. 4). For social media applications, ARON provides a convenient means of automatically attaching relevant additional information in an AR format to shared photos and videos. The ARON user can remain anonymous if desired.

ARON can fuse information transmitted via infrared light with video data from cameras in smartphones and other mobile devices to create dynamic AR imagery in real time, without reliance on cellular networks, Wi-Fi, the Internet, or other radio-frequency (RF) communication technologies.

Figure 4. ARON-equipped smartphone receiving outdoor optical signals.

ARON is also intended to augment sensor fusion in the digital vehicle platform (Fig. 5). It can operate in locations where no cellular signals or other RF-based communications are available. Optically beamed information can be detected by vehicles at ranges on the order of 1 km. ARON's directional, localized characteristics provide a unique capability to tailor the delivery of information, allowing ARON to easily communicate with moving vehicles. Multiple small ARON receivers providing 360^0 coverage could be mounted on vehicles, with no beam steering necessary due to the wide-angle field of view afforded by the optics. Received data can be selectively displayed on the vehicle console and/or stored in the vehicle central computer and filtered and forwarded as desired.

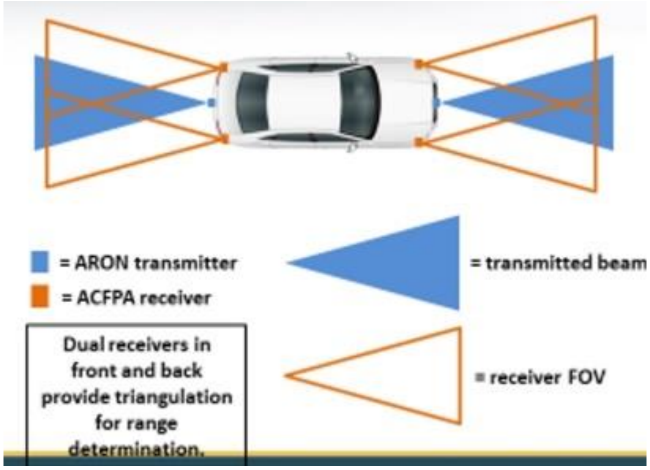

Figure 5. Vehicle equipped with ARON transmitters and receivers.

The solid angle tailoring of the data beam, i.e. directing the projection of the radiant energy only to where it is expected to be required, into a predefined area, allows us to reduce energy consumption by a factor of as much as 300, as compared to Wi-Fi, for an equal data rate of transmission. By tiling multiple transmitters and pointing them with angular separation, we can form a combined transmission beam that covers a zone of interest (for example, we can form a beam exclusively illuminating a zone along a street where reception coverage might be desired).

Multiple data streams are detected and processed by the focal plane array but if one of the redundant streams is interrupted then an adaptive (AI-style) algorithm which continuously analyzes the receiver data identifies which of the streams is being interrupted and switches the data processing to an alternate stream. Using this data processing algorithm it is straightforward to accommodate the simultaneous processing of 100 or more such streams on the focal plane array with a modest number of detectors (e.g., 100-1,000).

IV. THE ADAPTIVE COMMUNICATIONS FOCAL PLANE ARRAY (ACFPA)

Our Optical Narrowcasting System (ONS) utilizes Optical Receiver Modules (ORMs) to detect and receive optical data transmitted by Optical Transmitter Modules (OTMs). An ORM must include at least one Optical Beacon Receiver (OBR) and one Optical Signal Receiver (OSR). OBRs are designed to detect the presence of, determine the angular position of, and receive information from beacons, which are modulated optical beams transmitted by OTMs. Beacons contain information identifying entities (e.g., businesses, organizations, or private individuals) associated with OTMs. Once an OBR has detected, located, and received identifying information from a beacon, an OSR may be used to receive data from a signal beam transmitted by the same OTM that transmitted the beacon. A signal beam is a modulated optical beam that transmits data other than identifying information and typically utilizes a much higher average data rate than beacons.

In most cases it is desirable for an OBR to have a relatively wide field of view (FOV), because its purpose is to search for OTMs in situations in which little, if any, information will be available regarding their horizontal and vertical angular locations. A video camera is a suitable choice for use as a sensor for an OBR. Such a camera consists of an imaging lens with a focal-plane array (FPA) in its focal plane. The FPA is a 2D array of optical detectors designed to sequentially capture multiple frames of imagery at a frame rate usually on the order of a few tens of Hz. A narrowband optical filter will generally also be included in the optical train to improve the signal-to-noise ratio (SNR) by suppressing incident background radiation outside the beacon waveband. With the appropriate choice of imaging lens and FPA, such a video-camera-based OBR can have a sufficiently large FOV to provide a convenient means of searching for, detecting, and receiving data from beacons. The bit rate at which identifying information can be received from beacons by such a camera is limited by the Nyquist-Shannon sampling theorem to no more than half its frame rate. Since the information content of the identifying information is typically quite small (e.g., several bytes), this is not a serious limitation.

Although a conventional video camera is a suitable choice of sensor for use in an OBR, it turns out not to be suitable for use in an OSR. In most cases, an OSR must be capable of receiving data from signal beams at much higher average data rates than OBRs will typically receive data from beacons. Typically, data rates on the order of 1 Mb/s or higher may be required. A video camera used as a sensor in an OSR operating at a data rate of 1 Mbit/sec would have to have a frame rate of at least 2 MHz. The highest frame rates provided by conventional video cameras are on the order of 240 Hz, which is much too low. The ARON focal plane array (ACFPA, Fig. 6) differs from a video-style FPA in that it exploits the sparseness of the positioning of the communication signals on the FPA. So for example, in contrast to a typical 10 megapixel video FPA with a full frame sampling rate of 240 Hz, such as may employed by imaging cameras, ARON will employ a 100 element FPA array of detectors which is sampled at 2 megahertz. The total throughput of the receiver chip in pixels per second is comparable in both cases.

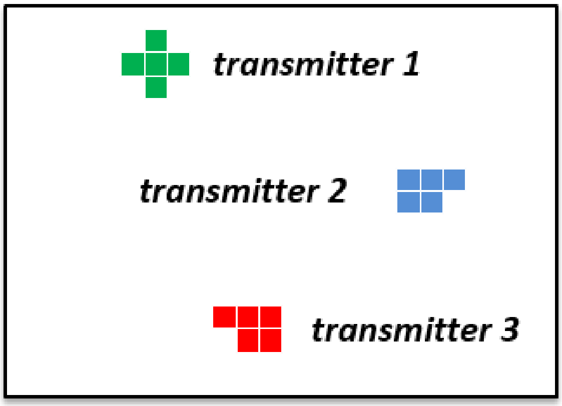

Figure 6. Multiple transmitter signals captured by the ACFPA.

Our Adaptive Communications FPA (ACFPA) provides the capability of receiving signal beams from OTMs at the required data rates. An Optical Communications Camera (OCC) consisting of an imaging lens with such a ACFPA in its focal plane will be capable of serving as both an OBR and an OSR, as long as the beacons and signal beams received from a given OTM do not overlap in time. As discussed above with regard to OBRs, a narrowband optical filter would most likely be included in the optical train of an OCC to suppress out-of-band background radiation. The ACFPA is designed to take advantage of the fact that the number of OTMs found within the FOV of the OCC will, in practice, be very small relative to the number of its detectors. The rate at which data is required to be output by the CFPA can therefore be substantially reduced by only outputting data from detectors that are actually receiving signal beams from OTMs, or from a subset of such detectors.

Detailed information describing the ACFPA chip design and the method of data processing is provided in US Patent 9,853,740 [9].

V. PERFORMANCE MODEL AND VALIDATION

To support our device design studies and provide a working physics tradeoff model for free-space optical communication, we composed a comprehensive signal to noise model to approximate the communications characteristics of an ARON-like device. The Technology Demonstration Unit (TDU) was then designed and fabricated using these modeled parameters to validate this model under real life test conditions. The methodology for the model and the detailed physics formulas are described in detail in the RCA Electro-Optics Handbook [10].

The model inputs are driven by the TDU system required capabilities. The outputs of the model flow into the hardware design parameters. In Section VI, we discuss the actual tested performance results of the TDU in comparison with the model.

The top-level requirements that drove our demo unit design are:

- A small IR transmitter with low power (under 5W total dissipation), using an LED source.
- Receiver to be integrated into smartphone Rx's case area near that of existing cell camera.
- Robust, no signal loss in communications to / between handheld phones with inherent physical jitter and occasional gross signal loss.
- Communication range up to 400 meters under ideal conditions passing HD video signals at rates higher than that required to watch in real time (i.e., able to quickly buffer excess error-free data).

The model assumptions are:

- Number of transmitter optics used, with 8° horizontal tilt difference between adjacent optics: 5.
- Output horizontal beam width produced by combined transmitter optics: $\Theta_{trans,horiz} = 40°$.
- Output vertical beam width produced by combined transmitter optics: $\Theta_{trans,vert} = 8°$.
- Peak optical output power (during transmission of a 1-bit) of infrared emitting diode used in each transmitter optic: $P_{src,max} = 1.4\,\mathrm{W}$.
- Center wavelength, for both transmitter and receiver: $\lambda_c = 850\,\mathrm{nm}$.
- Optical bandwidth, for both transmitter and receiver: $\Delta\lambda = 75\,\mathrm{nm}$.
- Bit rate: $BR = 1\,\mathrm{MHz}$.

ISBN: 978-1-68558-071-1

- Maximum allowable bit-error probability: $P_{error} = 10^{-9}$.
- Modulation scheme: return-to-zero (RZ) on-off keying (OOK).
- Duty cycle of signal pulse, defined as the duration of a transmitted signal pulse representing a binary 1-bit in units of integration times: $\eta_{mod} = 0.85$.
- Optical efficiency of transmitter optics, due to reflection and transmission losses: $\eta_{trans} = 0.80$.
- In-band atmospheric extinction coefficient: $\alpha_{atmos} = 0.1\,\mathrm{km}^{-1}$. (This value is based on Figure 7-3 of the RCA Electro-Optics Handbook, which shows horizontal clear-air attenuation coefficient as a function of wavelength. Atmospheric transmittance as a function of range r from transmitter to receiver is $T_{atmos}(r) = \exp(-\alpha_{atmos} r)$.)
- In-band spectral background radiance for use in computing photon noise produced by background radiation: $L_{back} = 500 \dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mu\mathrm{m}}$ (assumption of sun-illuminated background during daytime operation) or $L_{back} = 5 \dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mu\mathrm{m}}$ (assumption for nighttime operation).
- Optical efficiency of receiver optics: $\eta_{rec} = 0.8939$ (assuming uncoated polycarbonate lens).
- Full width of square field of view of receiver optics: $FOV_{rec} = 3.6°$.
- Refractive index of medium in which each detector in the receiver is immersed: $n_{det} = 1.00$.
- External quantum efficiency of each detector in the receiver: $QE_{det} = 0.7402$.
- Specific detectivity of each detector in the receiver: $Dstar = 4.06 \times 10^{12} \dfrac{\mathrm{cm} \cdot \sqrt{\mathrm{Hz}}}{\mathrm{W}}$.

The output intensity in the center of the beam produced by the five transmitters (with 8° horizontal tilt difference between adjacent optics) is 43.9 W/sr, assuming the optical output of each infrared emitting die is 1.4 W and neglecting reflection and transmission losses. When optical losses are included, this becomes 35.12 W/sr, where we have assumed each transmitter has an optical efficiency of 0.80. The maximum range for daytime operation is 415 m. The irradiance at this maximum range is:

$$E_{max,range} = \frac{35.12 \frac{\mathrm{W}}{\mathrm{sr}}}{(415\,\mathrm{m})^2} \cdot T_{atmos}(415\mathrm{m}) = 2.039 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{cm}^2} \cdot 0.959 = 1.956 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{cm}^2}.$$

The primary model output data included:

- Minimum transmitter exit pupil diameter, based on étendue conservation (~260 mm^2).
- Minimum signal Irradiance at entrance pupil – the minimum required optical power at input aperture of the receiver ($2e^{-8}$ $\mathrm{W/cm}^2$).
- Day and Night maximum operational range based upon bit rate (see Fig. 7 and Fig. 8)
- Day maximum operational range based upon Rx aperture (see Fig. 9).

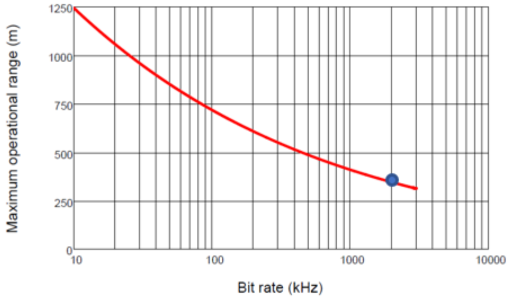

Figure 7. Maximum range vs bit rate (day).

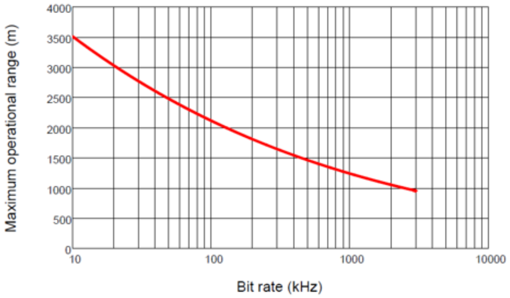

Figure 8. Maximum range vs bit rate (night).

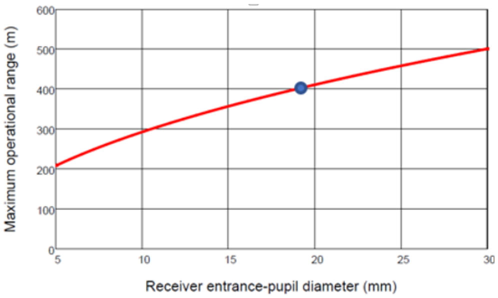

Figure 9. Maximum range vs aperture (day).

VI. TECHNOLOGY DEMONSTRATOR UNIT

To demonstrate the feasibility and functionality of the ARON concept, we have developed and fabricated a Technology Demonstration Unit (TDU) [11] that provides a communication channel in the 810-890 nm near-infrared (NIR) wavelength band, with a data rate greater than 1 Mbit per second and an operational range tested to work in excess of 200 meters in broad daylight. The unit consists of an optical transmitter (OT) and an optical receiver (OR), depicted in Figs. 10 and 12, respectively. This unit can transmit and receive HD video (and other digital files).

An ARON receiver's OBR measures the horizontal and vertical angular positions of ARON transmitters detected within its field of view (FOV) and then creates visual representations of the locations of the transmitters, including the identities of entities operating the transmitters. These representations comprise icons and text overlaid at the positions of these transmitters within live imagery produced by a video camera collocated with each ARON receiver. For example, the availability of information transmitted from a pizza restaurant may appear in the form of an iconic representation of a pizza accompanied by the name of the pizza restaurant, where the icon and text are overlaid at the location of the actual restaurant within the live video imagery. Controls are provided for allowing users to opt to receive high-bandwidth information of interest to them from the pizza restaurant's ARON transmitter or from additional ARON transmitters that may also be viewable in the FOV.

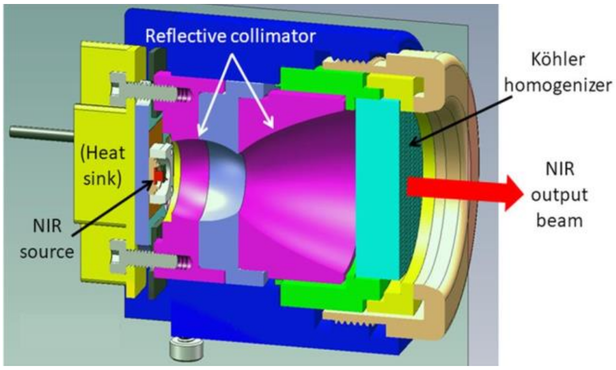

Figure 10. Cross-sectional perspective view of optical transmitter assembly for technology demonstration unit employing a nonimaging wineglass collimator.

The TDU's OT design comprises OT electronics, an incoherent solid-state NIR emitter, and a nonimaging beamforming optic. Our transmitter requires a mere 4 W of electrical power and has an exit-pupil diameter of 18 mm. The ARON system requires each OT to simultaneously transmit two types of modulated optical beams. The first type, referred to as a beacon, provides the means for an OR to: (1) detect the presence of OTs, (2) identify entities operating OTs, and (3) determine the positions of OTs within the FOV of the OR's visible-light camera. The second type of modulated beam, referred to as the signal, provides the actual information the operator of the OT wishes to send. Typically the average data rate transmitted by an OT in the form of signals will be much higher than that transmitted in the form of beacons. Temporary obstructions of the beam path that may occur due to moving obstacles are handled effectively using forward error correction algorithms.

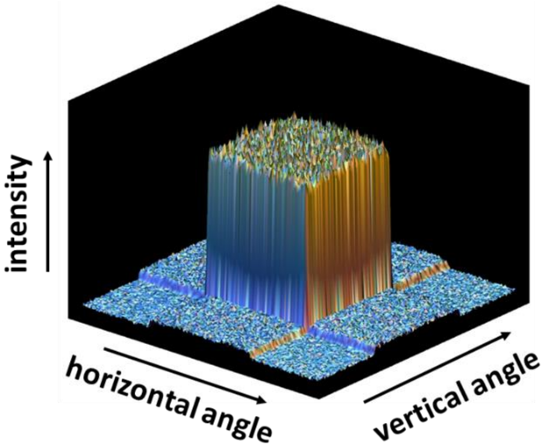

Figure 11. ARON transmitter forming a uniform 8°–square data beam.

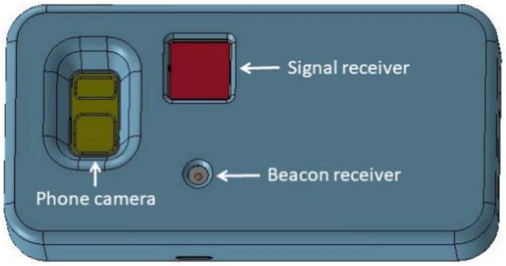

Figure 12. Optical receiver assembly of technology demonstration unit, mounted in a smartphone case.

To simultaneously transmit beacons and signals, the TDU uses a double-modulation scheme, in which a beacon having a data rate of 10 bits per second modulates a signal having a data rate greater than 1 Mbit per second. (ARON systems having far higher bit rates are feasible.) The double-modulation scheme has the advantage of allowing it to utilize a single NIR source and beamforming optic to simultaneously transmit both beacons and signals.

Fig. 10 depicts a cross sectional view of the NIR source and beamforming optic for the TDU's OT. The efficient, highly compact nonimaging optical design of the beamforming optic utilizes an advanced reflective collimator followed by a Köhler homogenizer to transform the output of the source into a NIR beam that is highly uniform within an 8°-square angular region (Fig. 11). The uniform square output beam allows copies of this optic, each with its own emitter, to be combined as modules to produce a customized tiled beam swath consisting of multiples of the 8°-square, arranged horizontally and/or vertically. A wide beam swath enables widely separated receivers to be able to simultaneously tune in to the transmission. The beamforming optical design used in the TDU is representative of a design that could be used for an OT mounted at a fixed installation (e.g., outside or inside a building) or on a vehicle. The wineglass collimator optic achieves a volume reduction factor of 2.5 compared to a conventional parabolic reflector.

The TDU OT electronics (not shown) consists of a smartphone interfaced via USB on-the-go (OTG) to a Universal Asynchronous Transmitter/Receiver (UART) which converts the byte-wise transmit data into a proprietary return-to-zero serial data format with a high level of embedded forward error correction. A current driver is used to modulate the solid-state NIR LED emitter with this data.

The OR design for the TDU comprises OR electronics, a beacon receiver, and a signal receiver, all mounted within a smartphone case and interfaced with a smartphone by means of a USB connection. An ARON app installed in the receiver smartphone provides the capability of combining beacon information received from OTs with live imagery produced by the phone's camera to create and display AR presentations.

The TDU's beacon receiver is a monochrome NIR video camera, which serves the purpose of detecting beacon data transmitted by the OT and using this data to determine the angular position of the OT within the FOV of the visible-light camera. The beacon receiver also receives and decodes identifying information encoded in transmitted beacons, allowing the OR to identify the entity operating the OT. Once a beacon has been detected, the processor determines its horizontal and vertical position within the visible-light camera's FOV and generates and overlays an augmented reality icon with identifying text at the correct location on the live video imagery, where the icon and text represent the identity of the detected OT obtained from its beacon. Multiple beacons can be handled. These functions could easily be integrated with a cell phone's existing camera if the OR is also integrated into the phone, as opposed to being in a cell phone case for the TDU.

The TDU's signal receiver uses a 6x6 array of square-aperture lenslets to concentrate flux onto a 6x6 array of silicon photodetectors. The outputs of all 36 detectors are summed, amplified, filtered and digitized to produce the signal output. The signal receiver has a 3.6°-square FOV within which it can receive signals. Since this FOV is much smaller than the FOV of the beacon receiver and the phone's visible-light camera, in order to receive a signal from a detected OT, the TDU user needs to manually tilt the phone until the OT is within the signal receiver's FOV.

Fig. 13 depicts the display screen of the receiver smartphone after the ARON app has been activated, showing the live video feed, overlaid with a central box representing the FOV of the signal receiver and an icon and text representing a detected OT. To receive a signal from the detected OT, the phone is tilted manually until the icon is located inside the box, at which time signal data will begin to be received. Receipt of signal data will continue as long as the icon is kept within the box. Once received, the app allows the user to view the signal data in various ways.

This section has described the elements of our technology demonstrator unit. In its planned production configuration, as an integrated internal component within a smartphone, an ARON receiver and optical assembly will ultimately occupy a footprint no larger than a conventional video camera. In this consumer configuration, employing an ACFPA chip, the phone will not require tilting to receive signals.

Figure 13. Display produced by augmented-reality optical narrowcasting app in technology demonstration unit's receiver smartphone.

The TDU's transmitter uses a single LED emitting into a wineglass collimator through a pair of micro-lens homogenizers, with dimensions and parameters very similar to those of the model. The TDU receive aperture was chosen to be ~19mm and bit rate at 1.1Mbit/s (good HD video transmission speed) was selected, both to support the 400m modeled maximum range goal. The TDU's receiver uses 36 fixed micro photodiodes in a 6x6 array, illuminated by 36 micro-lenslets also in a 6x6 array. These provide a large aperture while maintaining a very short system depth and are very close to those used in the theoretical model. The micro-lens array, an optical bandpass array and the detectors are mounted on a small circuit board along with the necessary support electronics. All are mounted in a case containing a smartphone used for the processing and display of the received information.

Results of outdoor tests with the Technology Demonstrator Unit hardware showed that actual daylight performance matched closely with that predicted by the theoretical model. Demonstrated maximum range was in excess of 200 m versus the desired 400 m.

Two known issues explain a large part of this range difference. The modeled receiver optics loss did not include additional attenuation in the band-pass filter, which has a pass-through limited to about 85% at our wavelength. Amplifier choice in the front-end electronics limited trans-impedance gain to about 75% of that desired for optimum signal to noise. In all, signal at the receiver was down at least 64%. Both of these losses can be mitigated easily in the future.

Finally, a commercial smartphone implementation would use a much smaller detector size than our TDU, and with an AFCPA chip architecture we estimate that the resulting detector noise could be lower by a factor of 4, which would lead to a realistic achieved signal reception range of 400 m for transmitted HD video.

VII. CONCLUSION AND FUTURE WORK

The availability of clear RF channels is fading. The yearly growth in demand for data bandwidth is fueled by the needs of IOT and Smart Cities. An open, unrestricted optical communications channel can provide space for at least some of this growth and enable a novel path for information expansion.

ARON's use of its tailored, configurable transmit areas for narrowcasting to desired locations, its ACFPA chip for angular multiplexing and detection of signals over a wide area, and its error correction and photonic cross-fire to solve the problem of obstruction, make it a new and novel platform to support this alternate data channel. ARON is intended to complement, rather than replace, the use of RF communications and to help ease future bottlenecks in a useful and elegant fashion.

Our main conclusion is that free-space optical communication using incoherent light sources is a much more practical proposition than has been believed to date.

Future work will entail the design and fabrication of the ACFPA chip and the integration of ARON into smartphone platforms and automobiles.

ARON is the subject of 21 US Patents.

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