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Introducing Agility in Hybrid Communication Systems and Sensors

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Abstract *– This paper presents a new approach in dealing with hybridization issues in communication systems or sensors. The thrust is to separate the logical network (sensor) infrastructure from the physical one. Here we show how we can exploit concepts such as persistent identification which we believe is crucial to be able to connect a variety of heterogeneous devices in a network that grows, and that is robust to failures. A vital characteristic of our architecture is the ability to accommodate a variety of heterogeneous devices and subsystems. Several examples of hybridization of sensors at the physical, logical, and network levels are presented and discussed.*

Keywords *– Hybrid, RF Photonics, Network architectures, photo-detectors, sensors*

I. INTRODUCTION

Currently, communication systems are composed of components and subsystems whose physical characteristics and capabilities are not only different but sometimes mismatched. Similar problems also appear in wireless sensor networks, especially when sensors are heterogeneous or they operate at different frequencies. In this work we show that rather than displacing each other, the original, current, and future devices are forced to share their capabilities within a hybrid framework. This presents us with the opportunity to design the future network to exploit the differences between communication components, sensors, and systems and linking them all into an existing network without having to design a new one.

Our current research is focusing on three distinct areas. First, at the component and interface level, the aim is to integrate the areas of RF and photonics to develop novel, optically-coupled antennas and sensors. This hybrid RF/photonics combination will eliminate the need of local oscillators, mixers, amplifiers and a host of other parts by directly feeding an antenna through a fiber at millimeter wave frequencies and thus increasing the bandwidth in modern communication systems and sensors. Different security applications require different types of sensors. Our aim is to have all these sensors interconnected and communicating with each other. This enhances any kind of security operation. Second, at the logical level, the aim is to produce a seamless communication between mobile and stationary sensors across multiple networks and through hybrid communication environments. The idea is not only to focus on the maximization of the aggregated hybrid resources that multiple networked sensors expose, but also on the effective integration of these resources into an ever expanding whole. Finally, at the network level, we are developing the theoretical platform for managing the complexity which arises from different sources: topological structure, network evolution, sensor connection and sensor diversity, and dynamical evolution.

The different levels of hybridization (component, logical, and network levels) are presented and discussed.

A. Component and Interface Level (RF Photonic sensor)

The *goal* here is to develop a new RF/photonic device that can be the central element for forming a new type of smart sensor at high microwave and millimeter wave frequencies.

Figure 1 depicts a conceptual schematic diagram of a transceiver element for RF sensor. It is fed by fibers carrying optical signals. As a transmitter, the optoelectronic device operates as a photodiode, while as a receiver the device operates as an optical modulator [1-4].

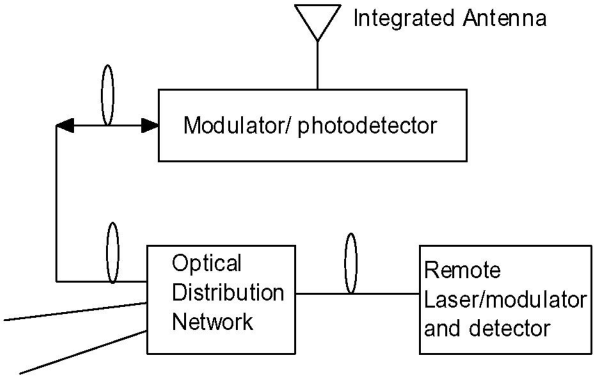
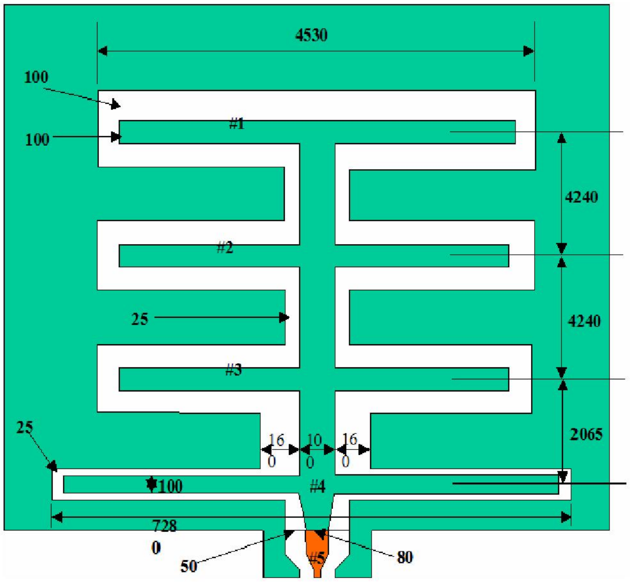


Figure 1. Schematic of one element of the antenna feed network, including optoelectronic transceiver, remote laser, optical detector and modulator for transmit/receive functions

The main emphasis here is to directly connect an antenna to the photo-detector without loss of power. Issues like biasing of the photo-detector through the antenna without affecting the performance of the antenna, novel CPW transmission lines with minimum return loss and finally the antenna/ array itself, pose serious fabrication and design challenges.

The choice of the antenna (sensor) design is based upon the constrains generated by the photo-detector (output impedance, physical dimensions), and the fact that the antenna and the photo-detector must be integrated together. The initial idea of building both (antenna and photo-detector) on the same substrate was dropped, since the material that maximizes the performance of the photo-detector was Semi-Insulated InP, which is very expensive to use as a substrate for the antenna. As a result, the newest designs are placing the photo-detector on SI InP (ε_r=12.5), and the antenna on the much cheaper glass (ε_r=5.7). The connection between the two will most probably be through wire bonding.

Another major issue that must be taken into account in the design of the antenna is the position of the contacts coming out of the WGPD. The output of the WGPD comes out in a Ground –Signal – Ground configuration, which leads to Coplanar Wave transmission line feeding. Since the three contacts (one positive and two negative) are on the same level, the ground plane must also be on the same plane with the antenna. Figure 2 show the antenna design that was chosen for operation around 18 GHz. Figure 3 depicts the measured and computed radiation patterns for the antenna connected to the photo-detector.



Figures 2. Antenna design including the photodetector

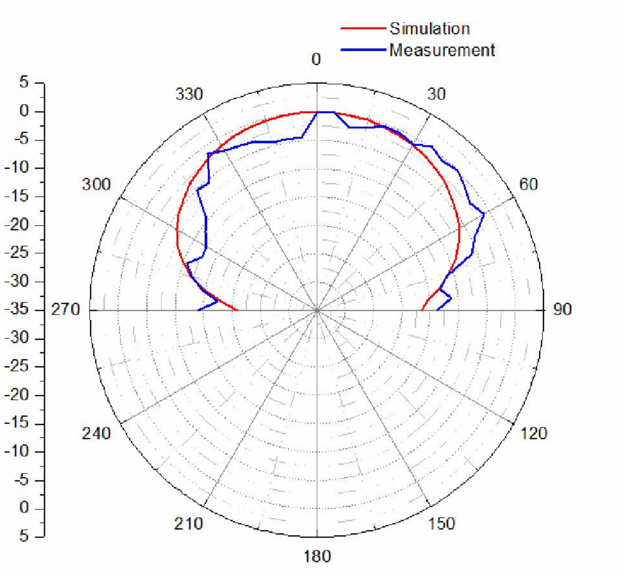


Figure 3. Measurement of E-plane radiation pattern of the photonic antenna. Simulation result (red) is also shown.

Figure 4 depicts an SEM image of a side-illuminated waveguide photo-detector (WGPD) that is used to convert the RF-modulated optical power into a microwave signal. The WGPD is a standard p-i-n device. Flexibility in the design of WGPD including optical coupling, optical absorption, transit time and capacitance provides the needed versatility to optimize the device design for a given application. The photo-detector is fed by an optical fiber

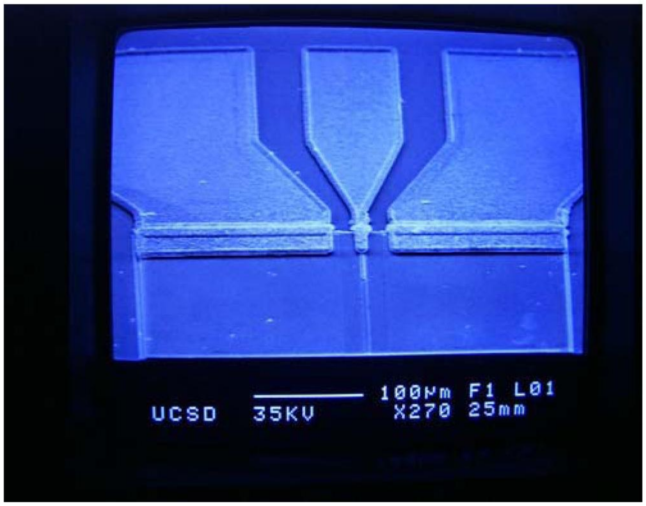


Figure 4. SEM image of the fabricated WGPD showing the CPW electrodes

The new hybrid RF/photonic system poses some challenging integration problems. A major design issue is the biasing of the photodetector to 10 Volts. The approach used was to run bias lines through the antenna, without any performance reduction and without any distortion of its radiation pattern. To solve the problem of leaking microwave energy in the biasing probe, a number of different filters were designed. This and further constraints will be presented and discussed.

B. Logical Level

At the system engineering and network architecture level, our work has focused primarily on the issue of mobile transient networks (ad-hoc and infrastructure networks) [5]. The main thrust behind this approach is to separate the logical network infrastructure from the physical one. In other words, and while the various components designed above are connected physically to other components across a hybrid network, the logical network aims at enabling seamless communication between mobile and stationary network entities across multiple networks and through hybrid communication environments as depicted in Figure 5. We have already exploited concepts such as persistent identification which we believe is crucial to be able to connect a variety of heterogeneous devices in a network that grows, and that is robust to failures. A vital characteristic of our architecture is the ability to accommodate a variety of heterogeneous devices and subsystems, thus providing an excellent candidate for designing and analyzing hybrid networks.

The integration of the heterogeneous networks depicted in Figure 5 is made possible through a logical abstraction that constitutes of a set of systems, components and mathematical notions. The most prominent of the concepts we introduced is the conceptualization of networked entities as persistent transient mobile entities that are uniquely and persistently addressed by the global system. In our approach to hybrid network abstraction, each communicating resource is mapped into a digital abstraction, which forms an entity that is uniquely identified by a persistent identifier. The digital entities are considered persistent and independent of their current physical and geographic attributes. This abstraction allows persistent addressing and communication between these entities regardless of their current association, location or means of communication in the hybrid environment. For example, the entity could move seamlessly from one network environment to another and still be seamlessly incorporated, provided it met the administrative requirements. Digital entities may be networked sensors, end-points, users, applications, sessions, backbone building blocks and even subsystems.

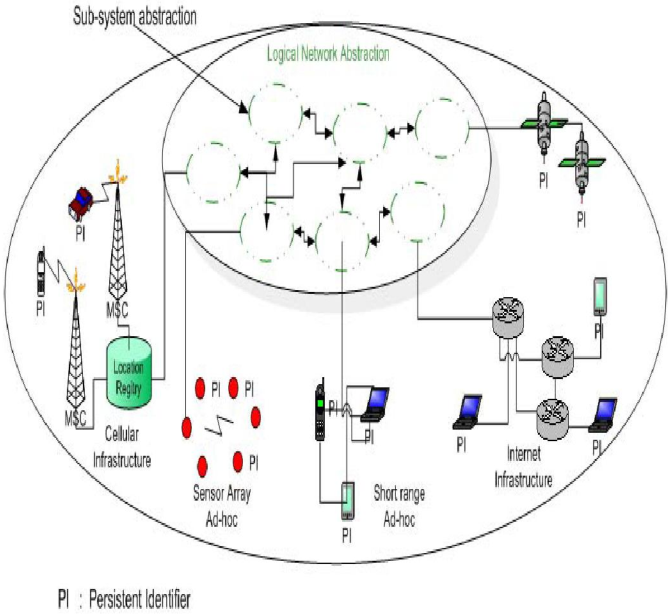


Figure 5. General Architecture Conceptualization

In recent work [6-7], we have experimented with users as digital entities in the context of VoIP, but the same concepts may be used in other communications applications. We have implemented a test-bed that allowed roaming users to be addressed with persistent identifiers regardless of their domain bindings or network attachment points. Users join the logical network to allow inter-domain registration, call routing and authentication. In the same sense, we envision any entity (sensors for example) to be able to seamlessly move between heterogeneous networks and still be reached and communicated with independent of the particular communication details. Our approach demonstrated more efficient security and routing mechanisms. So, as Figure 5 shows our roaming model whereby the roaming user *r_user* is now able to securely use the closest available server instead of communicating back to his home server which could be in another country. Figures 6 and 7 show the registration/authentication model and the call setup model respectively. In both figures, we depict the traditional sip flow (A) versus our proposed flow (C). The performance results are depicted in Figure 8, where we showed 5 to 7 times better performance for registration and as well a better call setup performance. Our roaming approach can be extended across hybrid networks to cell phones and sensors in communication networks.

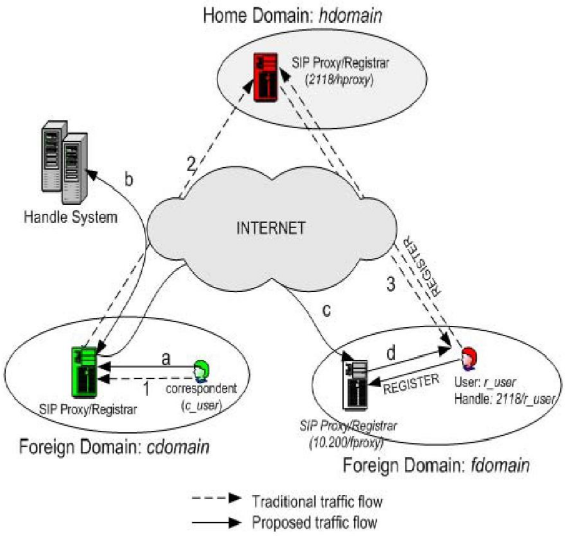


Figure 6. Roaming model

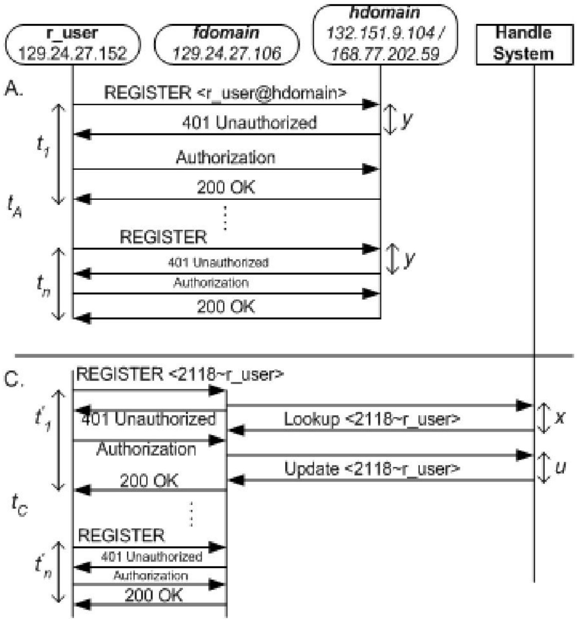


Figure 7. Registration model

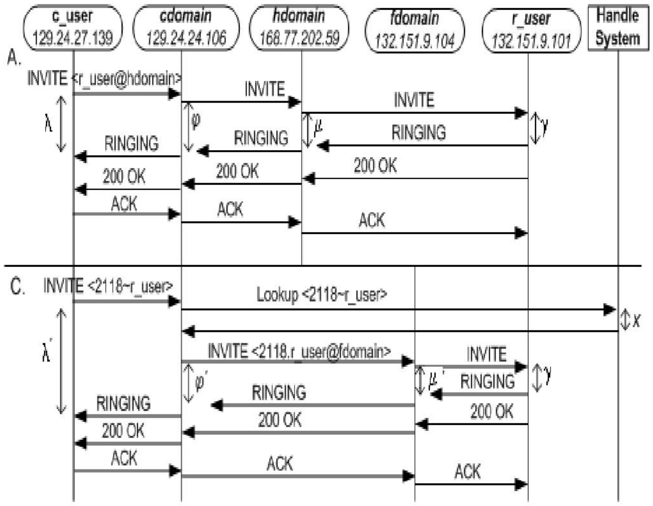


Figure 8. Call setup model

C. Network Level for Hybrid Communications

At the network level, given the high complexity of the overall system, one needs to develop the relevant theory to manage such complexity which arises from different sensors: topological structure, network evolution, connection and sensor diversity, and dynamical evolution. An effective way to model and control this complexity is by exploiting stochastic mathematical models. Depending on how these models are constructed, they create random structures that resemble what is observed in real natural, as well as in artificial systems. So far, we have focused on the application and extension of percolation theory and random graphs for the analysis and design of ad-hoc and sensor networks [8-11], and we plan to generalize these tools to hybrid networks. The first and most basic issue here deals with connectivity, which expresses a global property of the system as a whole: can information be transferred through the sensor network? In other words, does the sensor network allow at least a large fraction of the nodes to be connected by paths of adjacent edges, or is it composed of a multitude of disconnected clusters?

The second question naturally follows the first one and is directly concerned with the information flow: what is the network capacity in terms of sustainable information flow under different connectivity regimes? Finally, there are questions of more algorithmic and dynamic flavor, asking about the form of the paths followed by the information flow and how these can be traversed in an efficient way. What are the queues dynamics, and how the network can resist to failures and malicious attacks? The goal is to develop a general framework to study problems as the ones mentioned above in the context of hybrid systems.

One specific challenge of this line of research is to develop models of random graphs that describe the system in a structured way. Standard random graph models are typically “flat” in the sense that they consist simply of nodes and links that connect them, and all nodes are typically treated in the same way. On the contrary, in the hybrid sensor systems one must consider some notion of structure at the system level. Accordingly, we plan to extend random graph model to hierarchical random structures that are able to better describe the different levels of complexity in the sensor system.

II. CONCLUSION

Our work here addresses three levels of hybrid systems design: at the **component and interface level**, the aim is to integrate the areas of RF and photonics to develop novel, optically-coupled antennas and sensors. This hybrid RF/photonics combination eliminates the need of local oscillators, mixers, amplifiers and a host of other parts by directly feeding an antenna through a fiber at millimeter wave frequencies and thus increasing the bandwidth in modern communication systems. At the **network level** we exploit stochastic mathematical models as an effective way to model and control the complexity that arises from networking hybrid sensors together. Depending on how these models are constructed, they create random structures that resemble what is observed in real natural, as well as in artificial systems. Finally, at the **logical system level**, we present concepts for seamless communication between different sensors (mobile and stationary).

III. ACKNOWLEDGEMENTS

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