System Architecture for High-speed Close-proximity Low-power RF Memory Tags and Wireless Internet Access

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***Abstract* — We have developed an open architecture platform for implementing passive radio-frequency identification (RFID) tags with a mass memory for close proximity environment. Purposes for such mass memory tags are, e.g., multimedia files embedded in advertisements or logged sensor data on a low-power sensor node. In the proposed architecture, a mobile phone acts as the reader that can read or write the memory of these RFID tags. The architecture also enables creation of a new type of wireless internet access suitable for, e.g., internet kiosks. The architecture is designed so that development path to a full Network on Terminal Architecture (NoTA) is feasible. The wireless reading speed of the mass memory tags, demonstrated to be 112 Mbit/s, is in the range that a 3-minute 640×320-pixel video can be loaded from the tag to the phone in less than 10 s. Our solution supports Nokia's *Explore and Share* concept.**

Keywords — memory architecture; multimedia systems; RFID; telephone sets; RF memory tags; Internet connection

I. INTRODUCTION

Today's mobile phones contain music and video players, which make it possible for consumers to enjoy entertainment while on the move. Acquiring new multimedia content by downloading or streaming, however, is hampered by the high cost and slow speed of Internet connections, as well as by the fact that commonly used physical multimedia formats, such as optical disks, cannot be read with a mobile phone. Thus, to make acquiring new content easier, cheaper and less power-consuming, we propose a new technology based on radio frequency (RF) memory tags readable and writable by mobile phones [1].

RFID tags are increasingly a part of our life; transport, traceability, and secure access are some of the main uses of this close proximity technology today. Conventional machine-readable wireless tags, e.g., Near Field Communication (NFC) tags, normally have a very small memory in the range of hundreds of bytes or kilobytes. Some RFID standards include an option to have a flexible-use memory, but the capacity is low compared to factory-set fixed-content memory. Tag selection is based on reading the content in a selected tag memory address (e.g., tag or manufacturer ID). As the memory capacity of these tags is small, the amount of data to be transferred is also small and power consumption of RF communication is, thus, not a critical issue.

Various research groups have developed improvements to the commercially available RFID technologies. To overcome the storage capacity limitation of passive tags, Wu et al. increase effective tag storage sizes with proposed distributed RFID tag storage infrastructure (D-RFID stores) [2]. Tags would be distributed in space and time in this architecture. Ahmed et al. focus on RFID system unreliability and improvements in middleware for object tracking and object location with moving readers or tags [3]. As a result of their research, a virtual reader system architecture was introduced. Ying described a verification platform for RFID reader that utilized Ultra High Frequency (UHF) frequency [4]. This platform is applicable for customization with different RFID standards. Pillin et al. have developed a passive far-field RFID tag using the 2.45 GHz Industrial, Scientific and Medical (ISM) band, with a data rate of 4 Mbit/s on the range of 5.5 cm [5]. As an example of a proprietary solution, HP's *Memory Spot* tag also works on the 2.45 GHz ISM band and has demonstrated 4 MB memory and 10 Mbit/s data rate but only allowing a touch range [6].

The problems of low data reading rate and small memory size provided by contemporary RFID tags become emphasized if one considers mobile users reading multimedia files from tags embedded on, e.g., paper media. The attention span of a mobile user is about 10 seconds [7]. Within this period, the user could get a single multimedia content file from a memory tag. Considering a movie trailer, the file size for a 2-minute 640×320-pixel 30-fps (3 Mbit/s), encoded with H.264, would be around 50 MB [8]. The required minimum data transfer rate from the user point-of-view is thus 50 Mbit/s. This exceeds the maximum data rate available by the 13.56 MHz NFC technology, 848 kbit/s, by a factor of 60. Even the maximum data rate for NFC demonstrated on a laboratory set-up, 6.78 Mbit/s [9], is not enough. When users are getting used to NFC, the speed and storage capacity becomes quite easily a limiting factor. Thus, there is a need for a new high-speed touch-range RFID radio interface.

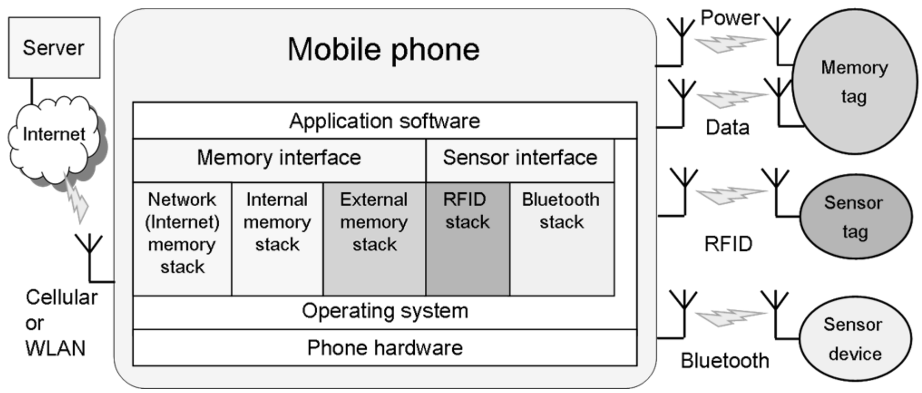

Figure 1. MINAmI Architecture [11]

The aim of our research has been to develop a high-capacity memory tag, which is wirelessly readable with a mobile phone and suitable for consumer markets in ubimedia applications [10][11]. The mobile phone acts as the user interface for reading and writing passive RF memory tags that contain a high-capacity memory (0.1–1 GB). The reasoning for the proposed technology was justified by modern trends in non-volatile memory technologies, according to which the power consumption, physical size, and price of memory are continuously decreasing. The technology presented in this paper supports Nokia's *Explore and Share* concept, a new way of transferring content (e.g., multimedia, maps, and applications) to a mobile phone [12].

Another use case for the technology presented in this paper is an Internet Kiosk, i.e., a short-range hotspot providing access to the Internet. Traditionally, an Internet kiosk is nearly always a computer connected to core network via a backhaul link that can be wired or wireless broadband. These Internet Kiosks are typically pay-as-you-go (credit card or pre-paid) or funded by advertisements presented within the kiosk screen.

Nowadays, accessing the Internet freely and securely has become critical for business and recreational needs. Personal wireless terminals (such as mobile phones or laptop computers) are, thus, associated with modern Internet hotspots based on wireless local area network (Wi-Fi) technology. These Wi-Fi hotspots are either free or paid by credit card when logging in and are widely deployed. Another kind of wireless Internet hotspot is femtocell-based [14], providing a local connectivity through cellular technology such as wideband code division multiple access (WCDMA). Conventionally, femtocells are designed for use in a home or small business to improve indoor wireless coverage. As Bluetooth is a competitive wireless solution especially from energy saving point-of-view, it has also been considered as one technology to enable wireless kiosks [15]. Moreover, NFC featured kiosks allow users to be connected and download multimedia content via NFC-enabled mobile phones [16].

All the wireless internet kiosk or hotspot types mentioned above share the demand of internal power within the phone, the power usage of the connection depending on the technology and status of the hotspot (distance, amount of devices connected etc.). If draining the battery of the phone is not acceptable (e.g., while travelling), a wired connection to a power outlet is needed.

In this paper, we describe and specify a network architecture, which enables mobile phones to read and write passive RF memory tags and use a RF memory tag based Internet connection. The architecture has been developed and demonstrated in the EU's 6th Framework Programme (FP) "Micro-Nano integrated platform for transverse Ambient Intelligence applications" (MINAmI) project [17], and thus the architecture is referred to as MINAmI Architecture. Important architecture requirements include openness, modularity, scalability, and energy efficiency. Openness and modularity are needed to support creation of novel applications and services by 3rd parties. Scalability of data rate is needed to enable evolution of the technology along with evolution of multimedia services. Energy efficiency is essential to enable passive operation of the tags as well as to save the phone's battery.

The paper is organized as follows. In Section II, we introduce the system architecture, along with a key component of the architecture, RF memory tags. In Section III, we introduce a novel dual-band radio subsystem and its hardware and software implementation. In Section IV, we introduce a new type of power-saving short-range wireless internet access for mobile devices and compare its power use to other available wireless internet access technologies. In Section V, we present the current status of implementation of the architecture, discuss possibilities for future development, and draw some conclusions.

II. MINAMI ARCHITECTURE

The proposed MINAmI architecture makes use of the mobile phone's capability of running software and providing several radio interfaces (Fig. 1). The architecture is modular, enabling simpler and faster development of new technical extensions (e.g., RF memory tags). Our architecture focuses on utilization of modularity on component level (e.g., where to plug memory tag functionality) and on communication level (e.g., how the available memory tags are utilized). At close proximity domain (range < 1 m), different tags are communicating locally with a mobile phone. In the present work we have concentrated on the RF memory tags. The sensor parts of the architecture (RFID sensor tags and Blue-

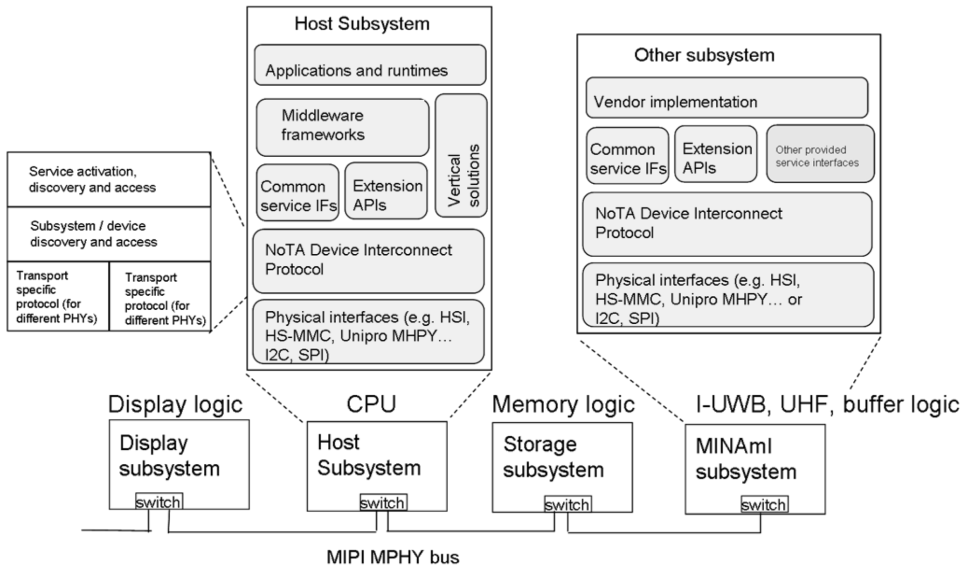

Figure 2. NoTA extension architecture for MINAmI subsystem, where HSI = High Speed Serial Interface; HS-MMC = High Speed MultiMediaCard: SPI = Serial Peripheral Interface bus.

tooth sensor devices) have been studied in an earlier project [18][19].

The main RF memory tag architectural design challenges include target platform performance obstacles, such as available bus operations (read/write) and power requirements, especially when drawing the line for autonomous operations in the described MINAmI architecture. The other challenge is minimizing changes to the existing system communication layering, only to the external memory stack block. The technological choices in the MINAmI system architecture were able to support both existing standard radios for low-rate sensors, and the high-rate high-capacity memory tags.

A. Network-on-Terminal Architecture (NoTA)

NoTA is a modular service-based system architecture for mobile and embedded devices offering services and applications to each other [20]. The concept is being defined in an open initiative. NoTA is also known as an open device distributed architecture, which allows direct connections between different nodes, within subsystem or between subsystems, supporting several physical interfaces within the device or between devices [21]. This architecture also supports both messaging and streaming services. The beauty in the architecture resides in modularity and transport independency. Direct connection between subsystems improves the efficiency as they do not necessarily require any processor involvement, when subsystems have all the needed functionalities available for their independent operations. Transport-specific portion is hidden underneath NoTA communication layering.

NoTA communication layering is built around transport-independent parts and it provides interfaces towards transport-specific parts (Fig. 2). Extension architecture with Device Interconnect Protocol (DIP) enables flexible open-source architecture for different hardware platforms. DIP provides logical links between a requesting subsystem and other subsystems or within a subsystem [21]. DIP is a device-level communication protocol that can be implemented for various physical interfaces ranging from MIPI (Mobile Industry Processor Interface) high speed serial interfaces and Universal Serial Bus (USB) to wireless interfaces, such as Bluetooth [22][23]. Another example of utilization of DIP is the Open Modem Interface Protocol [24].

NoTA host subsystem and neighboring subsystems are connected via the high speed physical interface. DIP adapts physical interfaces to the upper layers. It is the lowest layer that is common for all subsystems (i.e., also for MINAmI subsystem) and hides the physical dependencies underneath. Above DIP there is a common service interface used for resource management, file systems, and system boot-ups. Middleware frameworks, e.g., for multimedia, USB, and other applications, use a common service interface or extension Application Programming Interface (API). The architecture also takes into account vertical solutions, which may require an optimized protocol design for certain requirements that are tied to HW-specific applications.

NoTA subsystem structure takes into account possibility to add different types of independent service or application subsystems to the architecture, and the MINAmI subsystem forms one high data rate high capacity subsystem. When properly designed, the modular NoTA-based subsystem specification involves clear distinction of the system designer/integrator and vendor views of subsystem description and scenarios. Based on a provided subsystem specification the vendors test and validate their subsystem implementation and deliver them to the product designers for integration [25].

The MINAmI subsystem offers memory tag read/write, storage and local connectivity services to other subsystems within mobile device, and its architecture is compatible with NoTA communication layering. The MINAmI subsystem includes both the mobile phone (Mobile Reader/Writer) and the tag and all the relating hardware and software resources. Mobile Reader/Writer sees the contents of the memory of a

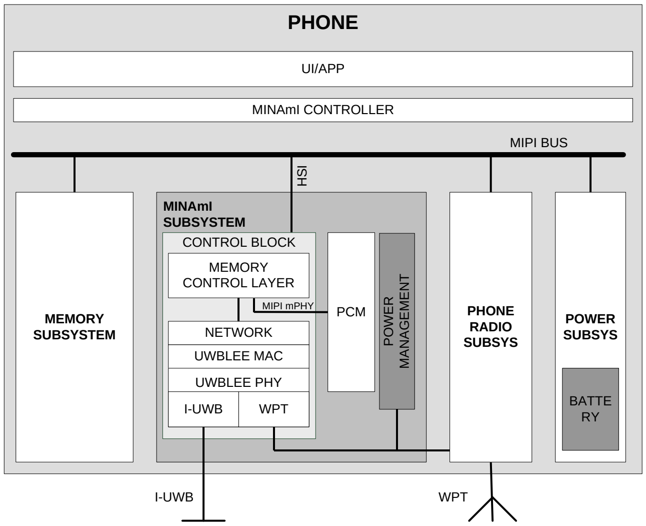

Figure 3. MINAmI Architecture on phone

passive RF memory tag only when there is an established connection, i.e., power field and data connection exists.

B. RF Memory Tags

The focus of our research has been on mobile-phone-operable memory tags suitable for consumer markets and ubimedia applications. The tag is developed as a part of our mobile-phone-centric architecture. Our memory tag development targets improving both transfer speed and storage capacity. These improvements give direct benefit for ubimedia users.

The target memory capacity of our memory tag has been in the range of gigabits and mobile reader/writer transfer speed to and from memory tag in excess of 10 Mbit/s. The same design platform is usable for both ends, for mobile phone platform reader/writer and for tag implementation. When designing the platform, various important design parameters, such as the selection of the used radio technology, were considered to provide an efficient and low-power solution for mobile reader/writer and tags.

It was important to make sure that connectivity technology is simple enough for the user, e.g., it should facilitate easy content selection (see Section III.D). Memory tag content selections should be based on metadata (e.g., filenames, file content types, file content keywords). Due to the large memory size, power consumption for memory access is a critical design issue, both for reading and writing the memory tag. To be successful on the market, RF memory tags for ubimedia must be passive to make them as small (size) and cheap as possible, and to achieve autonomous usage with minimum maintenance (e.g., usage without charging of battery). This severely limits the power budget. On the other hand, a short communication range (even touch) is sometimes preferable to make it easier for the user to physically select the tag. An RF memory tag will be read many times by different users, but written more rarely – in some cases, only once. The memory unit must work reliably even with several consecutive read cycles. A limited write throughput due to power constraint is not an issue, as data is rarely written by the users.

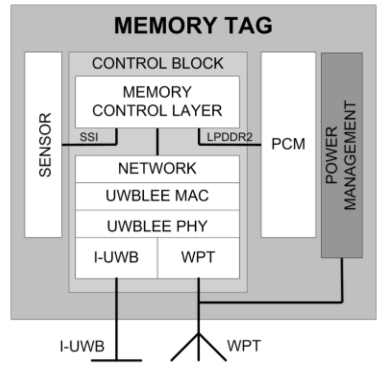

Figure 4. MINAmI Architecture on a RF memory tag

III. UWB LOW END EXTENSION

As memory tags have high data storage capacity, a high-speed radio is needed for communication to enable reading even all the contents of the tag in an acceptable time. Currently available mobile phones contain several radio transceivers, such as cellular, Bluetooth, and Wi-Fi, along with NFC. Most of the technologies are made for well-established communication between active devices, consuming a relatively large amount of power. These technologies are also not inherently designed for ad-hoc, possibly one-time, connections between devices that have not communicated with each other before, resulting in long latency in establishing the communications. For example, in an environment with many unknown Bluetooth devices, the Bluetooth connection setup latency can be over 10 seconds [26]. NFC enables communications between an active and a passive battery-less device and is physically more selective; its communication range is almost in touch. However, it has severe limitations in data transfer speed.

To provide higher data rates, a wider frequency band available on higher frequencies needs to be used. On the other hand, the efficiency of wireless power transfer (WPT) decreases as a function of center frequency. To solve the problem of providing high-speed communication (high frequency needed) while simultaneously providing power wirelessly to the tag, a dual-band radio interface has been proposed [27]. One narrowband signal on RFID frequencies (e.g., RFID frequency bands globally available between 860–960 MHz) is used to power the tag and to provide a mutual clock reference for both ends of the communication link, whereas the communication link itself is based on impulse Ultra-Wideband (UWB) technique to provide a high communication bandwidth and scalability for even higher data rates.

As the selected RFID frequencies are approximately in the same frequency range as Global System for Mobile Communications (GSM) or WCDMA 900 MHz, in the reader there is a possibility of integrating the WPT function to the existing Phone Radio Subsystem, as presented in Fig. 3. In that case, Phone Radio Subsystem is designed so that the WPT Physical (PHY) Layer function may request a direct access to control the activation of the narrowband transmitter. Especially, the time-domain interleaving of different functions is important to support co-existence of GSM/WCDMA and WPT signaling.

The architecture of the RF memory tag (Fig. 4) is similar to the MINAmI subsystem on the mobile phone. For simple RF memory tags, no network layer implementation is needed to take care of the point-to-point communication between the reader and the tag, and therefore is handled on Medium Access Control (MAC) layer.

As an option for use-cases like data-logging sensor devices, the memory control layer provides a sensor interface. During the sensing, the sensor data is stored to the Phase-Change Memory (PCM) block and the low data-rate data capturing is powered from a battery or with energy harvested from the environment. For fast downloading of the logged data, the reader powers the sensor tag wirelessly.

A. Hardware architecture

The hardware, both the radio front-end and the memory, of the RF memory tag needs to run on the energy scavenged from the UHF transmission of the mobile phone. This subsection describes the enabling technologies: low-power high-data-rate radio front-end and low-power high-capacity high-speed non-volatile memory.

1) Radio Front-end

As presented in [27], a very simple super-regenerative transceiver architecture can be used in impulse UWB communication to achieve required data-rates over short distances. In contrast to conventional impulse UWB transceivers [28], there is no need for multipath recovery over the distances below 30 cm. This decreases the requirements set for the UWB transceivers. This is used to minimize complexity and power consumption of the transceivers. In the aforementioned super-regenerative transceiver one super-regenerative oscillator is used alternately both to generate transmitted pulses and to amplify received pulses, and no linear amplifiers are needed. Thus, the architecture utilizes the inherently low duty cycle of the transmitted impulse UWB signal also in reception the receiver being fully active only exactly during the detection of incoming pulses.

Synchronization is often problematic in impulse UWB systems because of the low duty cycle and pseudo-random timing of pulsed signal, and due to frequency drift and differences of reference clocks between the transceivers. In the proposed system the frequency synchronization between the reader and tag is achieved thanks to the mutual narrowband WPT signal, which is also used as the reference clock. The phase synchronization of impulse UWB transceivers is also easier to achieve due to decreased need for pseudo-random time-coding of pulse patterns.

The transceiver structure supports simple On-Off-Keying (OOK) modulation. The data-rate and power consumption is also scalable depending on the power level available for the wirelessly powered tag. Due to the simplified transceiver structure, targeted ultra-low power consumption and partial exploitation (500 MHz) of full UWB band (3.1–10.6 GHz) authorized by Federal Communications Commission (FCC) for unlicensed use, the impulse UWB system referred here is called UWBLEE (UWB Low End Extension).

Altogether, the optimized transceiver architecture makes it possible to achieve required high data-rates with a low power consumption performance (a few mW) suitable for WPT. As a proof-of-concept, a complete wirelessly powered RF front-end implementation of the super-regenerative transceiver is presented in [29] and [30] by using a single super-regenerative oscillator for transmission and reception. The front-end implementation supports data-rates up to 112 Mbit/s with the energy consumption of 48 pJ/bit in reception and 58 pJ/bit in transmission. The feasibility of the ultra low power consumption in high data-rate two-way communication is verified with an integrated RF front-end implementation based on the symmetrical transceiver architecture proposed earlier [27]. A 900 MHz WPT signal is used as a mutual clock reference and the communication is done over an impulse UWB link at 7.9 GHz center frequency. The scalable data-rate of UWB link up to 112 Mbit/s has been demonstrated as well as robustness against narrowband interference.

2) Non-Volatile Memory (NVM) technology

The main reason to pick up PCM in favor of any other memory technology [31] were the benefits of PCM technology, e.g., the estimated high number of read/write cycles as 1×10^6, which consequently results in need of no or just a lightweight wear leveling algorithm, and the bit alterability – lack of need of block erase cycles (as with flash memory) when data should be stored. From the perspective of technology lifecycle PCM stands now between a pure innovative technology and early adopters' stage. There are several 90 nm products [32] on the market already and more to come.

Aggregating main memory characteristics in comparison with NAND/NOR flash technology and dynamic random-access memory (DRAM) execution memory, PCM stands between those two in terms of cost per die. It is characterized as 5.5 F^2 factor in cell size having the same wafer complexity as DRAM technology. Currently only Single Level Cell (SLC) PCM is available, though Multi-Level Cell (MLC) PCM is on the way out, which can substantially extend the density and, justify the cost structure [31]. Thus, the application range can be quite wide from external usage (cards, keys) and wireless applications (RF memory tags) to high performance computing applications (caches, code execution, data storage). Considering reliability characteristics it is important to note that PCM technology gives more than 10 years retention ratio that can be extended even further, if necessary, by proper bit error management.

PCM has performance characteristics such as read & write latency and read & write endurance almost as good as DRAM, while giving clear benefits through the non-volatile nature of PCM technology. PCM has a low system-wise energy consumption (~0.2 mW/pF read, <1.25 mW write) ~<1 mW/GB of idle power, access time comparable to DRAM (~85 ns), with read latency 50–100 ns, write bandwidth from 10 to 100+ Mbit/s/die, write latency 500 ns – 1 μs, various packaging and die stacking solutions, high-speed low-pin-count low-power interface solutions, and maturity of the technology as such.

The PCM technology highlights provide clear reasoning for the selection of such technology for the RF memory tag application, preserving the opportunity to justify it even further when some other application should be designed.

B. Software Architecture (protocol stack)

The MINAmI software architecture (protocol stack) is designed to be modular and scalable. The protocol stack is based on three layers: Network Layer, MAC Layer, and PHY Layer. The APIs of the layers are open for 3rd parties. These layers will be presented in the following sections. The protocol stack has been developed taking into account future compatibility with NoTA architecture. Care should be taken to have a clear implementation path towards the final architectural (NoTA) solution.

1) Network Layer

Network Layer will first only provide point-to-point connections regardless of state. In future, also applications using multiple targets could become feasible when MINAmI Subsystem is in active mode. If a point-to-multipoint network protocol is needed, nanoIP is easily implementable [18][33]. However, to get full internet support classical IP protocol may be valid, and more common in networking devices. In the final architecture (NoTA) solution, the network layer will consist of Device Interconnect Protocol (DIP), as a middleware, which guarantees the compatibility with NoTA. In DIP protocol, it is possible to select, which transport mode and network is used. For example DIP TCP L_IN (transport selected) is ready to be used within one device and between several devices in a sub-network as such. Multicasting must be enabled in IP interface in order for device discovery to work. Nodes, which are in different sub-network, cannot be detected [21].

Packet size is an important parameter and depends on what is feasible for MAC and PHY layers. Upper layer packets are segmented and reassembled and this is dependent on what kind of packet sizes the system supports.

2) MAC Layer

The MAC of the novel dual-band radio interface has three different operational modes: the passive mode, where no internal power source is available or used; and the active and semi-passive modes, where internal power source is available. Tags on battery-less objects without power wire connection (e.g., implanted on paper) are passive.

In the active mode, the mobile phone actively searches and selects the target tags, sends the targets the WPT signal for powering and for frequency synchronization of the communication link, reads/writes data on the tags, and closes the connection to the target when active connection is no longer required. This operation can be an automatic feature, or enabled by the user (initiating the application for reading and writing the tag). In the semi-passive mode the phone receives data sent by an outside device, but powers itself, allowing a longer communication range, which would otherwise be limited by the WPT link. In semi-passive mode, however, the initiator device takes care of the synchronization of the I-UWB communication link.

Active mode states are used by battery-powered mobile devices, whereas passive mode states are applied for passive devices and tags. In passive mode, possible connections are powered by an outside device with WPT. In the passive

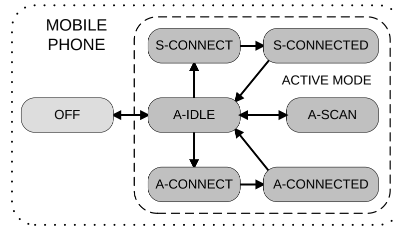

Figure 5. Active (and semi-passive) UWBLEE MAC states on a mobile phone. Active states denoted with A, semi-passive with S.

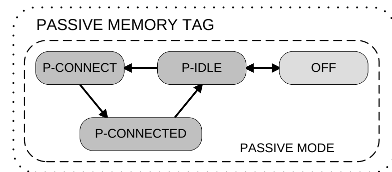

Figure 6. Passive UWBLEE MAC states on a RF memory tag.

TABLE I: UWBLEE PHY IN DIFFERENT MAC STATES

	MAC mode		
	Passive	***Semi-passive***	***Active***
I-UWB	Transmit / receive		
WPT synch	Receive	Receive	Transmit
WPT power	Receive		Transmit
Power source	WPT reception	Battery	Battery
Remarks	Being read / written		Reading / writing other devices

operating mode, the default state (when powered by an outside device) is P-IDLE, i.e., ready to receive any data, after the boot-up sequence.

The main operational states of UWBLEE MAC are shown in Figures 5 and 6. In addition to the shown directions of movement from state to state, there need to be possibility of built-in error recovery operation from any operational state to the corresponding idle state (A-IDLE or P-IDLE). For the applications requiring higher security, a suitable security protocol can be applied for the ongoing data transmission.

3) Physical Layer

UWBLEE PHY layer controls both the I-UWB communications and Wireless Power Transfer (WPT) transmission. Depending on the operational mode (active or passive) WPT link is used to send (or receive) power and/or to provide the clock reference signal.

UWBLEE PHY is divided to two sub-blocks: I-UWB PHY and WPT PHY. I-UWB PHY controls the Impulse-UWB radio interface and WPT PHY controls the Wireless Power Transfer interface. I-UWB PHY and WPT PHY are coordinated by UWBLEE PHY so that I-UWB transmission is synchronized with the WPT transmission.

The function performed by UWBLEE PHY is defined by UWBLEE MAC, as shown in Table 1.

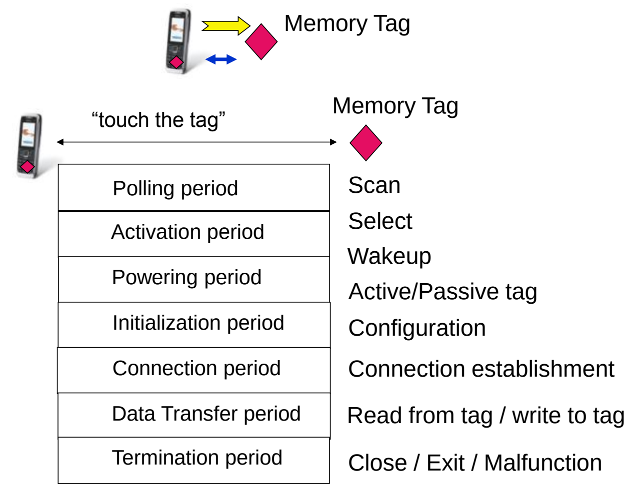

Figure 7. Mobile reader/writer to RF memory tag communication sequence

C. Packet-level Communication

The MINAmI subsystem communication between active mobile reader/writer and passive RF memory tag consists of periods shown in Fig. 7. In the beginning, there are no tags within the mobile reader/writer local connectivity coverage. If the mobile reader/writer detects a tag during the powering period, it tries to scan all tags available (in the polling period) and – based on the current selection criteria – choose one with whom to communicate (in the activation period). The right tag is found by scanning the coverage area, synchronizing communications with the tags, and selecting the right tag. After this selection, connection and device configuration is executed in the initialization period to set communication parameters, to specify packet level parameters (e.g., length, memory allocation). The connection period is initiated when connection between mobile reader/writer and selected tag is established. This is followed by the data transmission period, reading and/or writing selected content from/to tag. After successful data transmissions, in the termination period, connection is closed or continued with another read/write operation to the tag.

Basic connection procedure between a mobile reader and a tag is described in Fig. 8, which also identifies affected internal entities, e.g., MINAmI server, memory management, and communication entity (MAC and PHY layers). For the air interface, the data from/to the non-volatile storage memory (PCM) is buffered into a DPRAM buffer memory equal to the maximum packet size transferred over the air.

D. File System Design

The mobile phone can read tags and with writeable tags the phone can also write all or parts of their contents. The communication capacity between the mobile terminal and the RF memory tag is targeted to exceed 50 Mbit/s (as discussed in Section I). Plug-in software (External memory stack in Fig. 1) is required to facilitate seamless use of the tag memory for mobile phone applications.

The memory tag can be used as an extension to the local file system of the reader (e.g., mobile phone). The memory tag can be either a passive and cheap one (Fig. 9) or an active

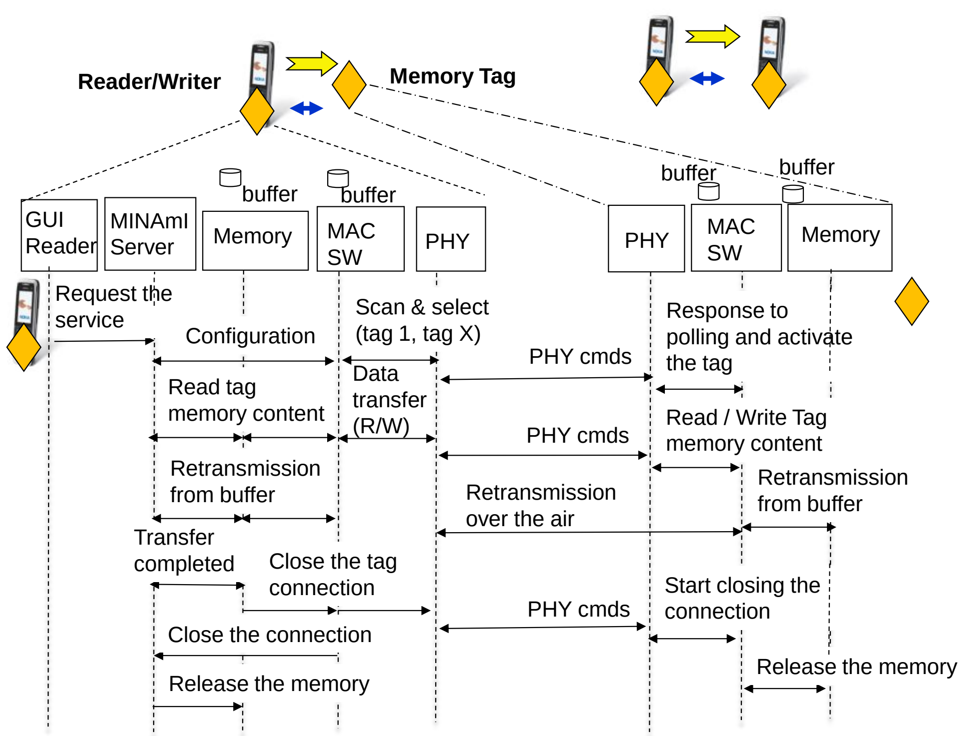

Figure 8. Basic MINAmI subsystem communication setup sequence

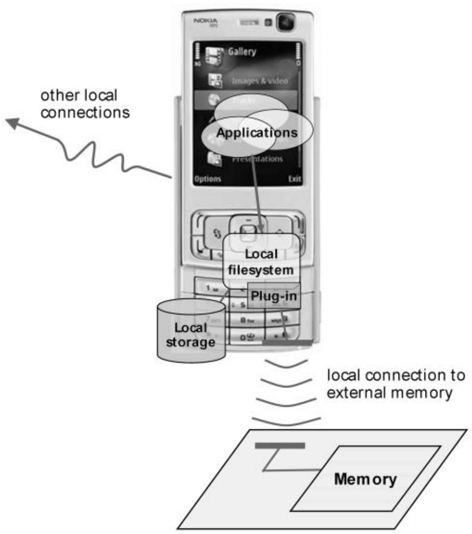

Figure 9. File system view of a mobile phone reading a passive memory tag: a cheap tag without its own processor [11].

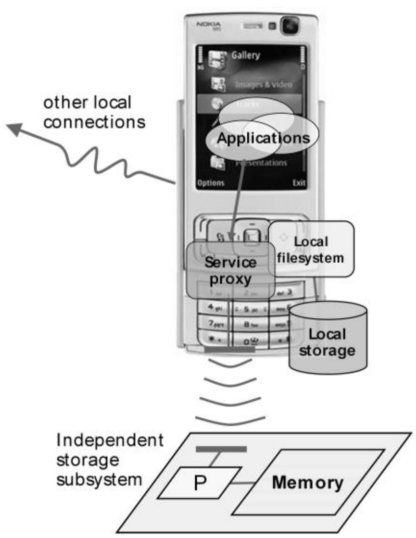

Figure 10. File system view of a mobile phone reading a passive memory: a more expensive tag with its own processor [11].

one, including an own power source and thus being more expensive (Fig. 10) [11]. Plug-in software in the file system of the reading device handles the connection to the memory tag. Storage space on the memory is mounted on the local file system in the same way as any detachable storage. The volatile nature of the connection causes overhead in maintaining the file system view in the reader/writer device. This kind of RF memory tag would be suitable for e.g., a concert ticket containing implanted multimedia available to be read with a mobile device.

Adding a processing element to the memory simplifies the connection. An ultra low-power processing element can process the access requests independently and even provide some more advanced services like metadata-based queries [34]. A service proxy relays the service interface of the memory directly to the applications running on the accessing device. The volatile nature of the connection is not a problem

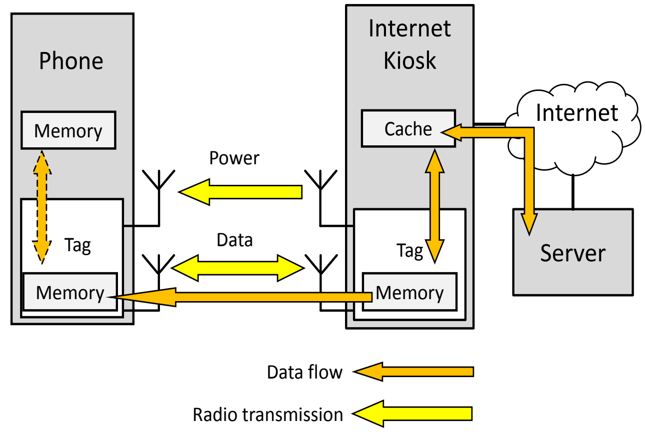

Figure 11. Mobile phone operating in passive or semi-passive mode to download data through an Internet Kiosk.

if the server is made stateless and transactions atomic. This type of RF memory tag will be able to support more complex use cases.

Device internal modules need to support NoTA to get full benefit of subsystem independency and still give a fast connection between subsystems. This interconnect architecture allows future extensions for modules within one device.

IV. WIRELESS INTERNET ACCESS

Service providers and device manufacturers are continually challenged to deliver value and convenience to users by, for example, providing compelling network services. These services can include selling and distributing content. More effective and efficient way is needed to distribute the content. As a complementary solution to address the issue, RF memory tag based internet kiosk can provide the ultra-fast and power-efficient connectivity for downloading multimedia content, which is beneficial especially when ad-hoc downloading large amount of content.

The multimedia content such as audio and /or visual content can be ordered by users and/or pre-downloaded by service providers. The content is preloaded into a radio frequency memory tag installed in the Internet kiosk as shown in Fig. 11. When a user stays in the range of UWB, a request is generated for the content stored in the memory tag. The Internet kiosk initializes wireless transmission to push the content from the memory tag to the user's terminal in response to the request via UWB [35]. The Internet kiosk can be deployed in public spaces for users to access ubimedia applications, e.g. downloading magazines, newspapers or audio/movie multimedia for recreation in airports.

As discussed in Section III, most of the technologies, namely Wi-Fi, cellular, Bluetooth and NFC are designed for well-established communication between active devices, which result in relatively high power consumption and a long connection establishment time. In our RF memory tag based solution, MINAmI subsystem is within mobile devices to provide necessary connectivity to the Internet kiosk, memory tag and storage for downloading ubimedia content as illustrated in Figs. 3 and 4. The subsystem can be standalone and operational without maintaining from main application bus in mobile devices and consuming extra system resources.

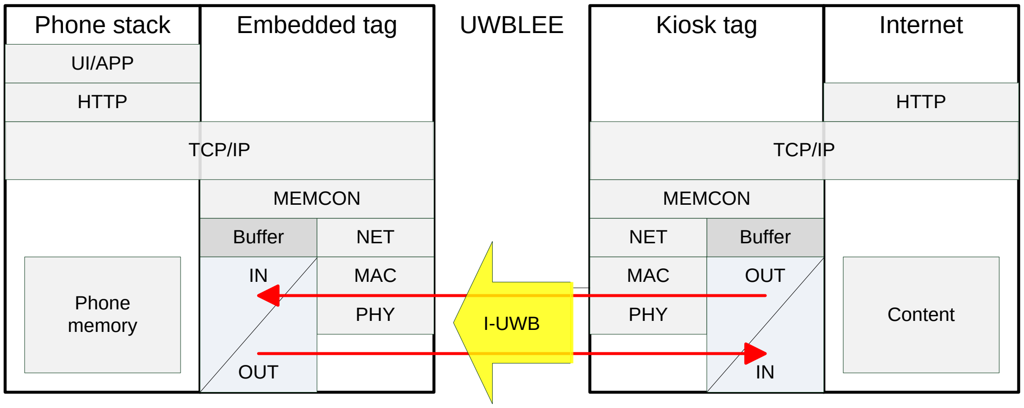

Figure 12. Schematic layout of the communication system when a mobile phone connects to the Internet via a memory-tag-based Internet kiosk.

Besides, the subsystem can be powered off until a new request arrives and it would not suffer from long latency in establishing a new connection.

In this architecture, the mobile devices could operate in either semi-passive or passive mode instead of active mode. The downloading is powered by phone battery in semi-passive mode and it is powered by the Internet kiosk in passive mode. By running in passive mode, the memory tag is powered by the Internet kiosk, and the mobile devices only consume energy to receive content and write these data into memory. This yields a great potential of energy saving on mobile devices especially when downloading large amount of content.

From the communications point-of-view, under the end-to-end Transmission Control Protocol – Internet Protocol TCP/IP layer there is a memory connection (MEMCON) layer connecting the content of the phone tag and the kiosk tag (see Fig. 12). The memory within the tags is divided into at least two parts, of which one is outgoing and one incoming data area. The master device (in the case of the kiosk, the kiosk tag) reads automatically the data in the outgoing data area of the slave device (phone tag), copying it to the incoming data area of its own memory. The data is then read by the controlling software and possible application level commands (e.g., fetch content from web address) found are then carried out. The reply data (e.g., data fetched from the web address) is then written to the outgoing data area of the kiosk tag, which is automatically copied to the incoming data area of the phone tag. Thus the memory connection layer automatically reads and copies the outgoing data from each device to the incoming data area of the other device. The upper layer control software of each device then moves the data further to the Internet services (Kiosk) or phone memory (phone) to be used by the application requesting the data. From the point-of-view of an application on the phone requesting data (e.g., Internet message access protocol (IMAP) email download) from a service provider in the Internet, there is a TCP/IP connection available.

The solution also makes possible providing an instant content download possibility by preloading data from an Internet service to the phone, e.g., a web page, digital magazine, or email account contents. In that case, the kiosk can be labeled with the logo of the corresponding service, telling the user what he/she would get by touching the logo with the phone. As the data is pre-loaded to the tag, the speed of delivery is only affected by the speed of the UWBLEE connection and data handling and displaying within the phone.

A. Comparisons

Maximized throughput and minimized power consumption are critical requirements in order to extend battery life of mobile devices. Given the scenario of Internet Kiosks, various radio technologies could be utilized to provide Internet connectivity from mobile phones to the Internet Kiosks. Normally, Wi-Fi and femtocell focus on local coverage. They are widely deployed and typically used by mobile devices. However, they are not always the most viable solutions. When traveling abroad, data roaming over cellular network, such as 3G (WCDMA) may be very expensive.

3G and Wi-Fi typically drain battery quickly on mobile devices. Since the fixed overhead of transmission is significantly high when the radio interfaces are in communication state. Once the radio interface is on and operates in active state, most of the power is consumed on circuits and does not matter how many data are sent or received over the interface. Especially in 3G networks, the radio switches to the higher power states, DCH (Dedicated Channel) or FACH (Forward Access Channel) from IDLE state, when the network is ac-

TABLE II. COMPARISON OF POWER CONSUMPTION OF DIFFERENT DATA COMMUNICATION TECHNOLOGIES

Wireless interface	**Max data rate**	**Maximum application throughput**	**Power consumption**	**Energy consumption**
	Mbit/s		***mW***	***nJ/bit***
3G	7.2	~5	~850	~170
IEEE 802.11g	54	~20	~500	~25
Bluetooth 2.0+ EDR	3	~2.1	~60	~28
NFC	6.78	848 kbit/s	~30	~35
UWBLEE	112	~50	~5.4	50-60 pJ/bit (*

*) The value 50-60 pJ/bit is only for the RF front-end of UWBLEE

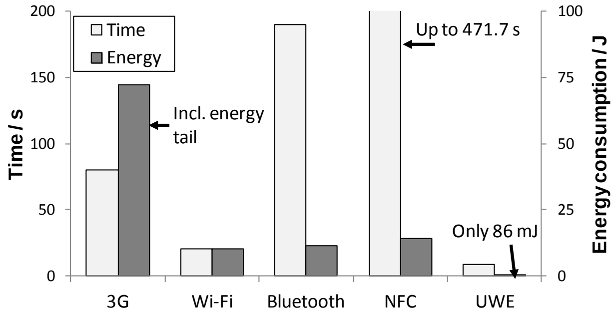

Figure 13. Time and energy consumed of using different radio technologies when downloading 50MB movie trailer.

tive [36]. Based on our measurements on a Nokia N900 phone, IDLE state is considered as low power states, which consume only around 30 mW. The state of Cell FACH consumes around 400 mW and the state of Cell DCH consumes around 800 mW. According to 3GPP standard, there are so called inactivity timers managed by the radio network controller (RNC). The transitions between the different states are controlled by inactivity timers. Transitioning from the high to the low power state immediately after a packet is transmitted, the device transitions only when the network has been inactive for the length of the inactivity timer. This mechanism serves two benefits: 1) it alleviates the delay incurred in moving to the high power state from the idle state, and 2) it reduces the signaling overhead incurred due to channel allocation and release during state transitions. Since lingering in the high power state also consumes more energy, network operators set the value of the inactivity timer based on this performance/energy trade-off, with typical values being several seconds long. However, these timers result in extra energy consumption even if there is no data to be sent or received since the radio has to wait for the timers to expire. The energy consumption is defined as tail energy [36].

To overcome energy consumption constraint in 3G and WLAN networks, short-range radio communication could be used. There are several radio technologies that can be considered for the use of Internet Kiosks. For instance, Bluetooth, NFC and UWBLEE where the mobile phone could operate in semi-passive mode in which communications are powered by the Internet Kiosk.

In order to reduce power consumption and extend battery life of mobile phones, battery-operated devices require being equipped with a radio technology with high bandwidth and low power consumption. Therefore, the mentioned radio technologies are taken into consideration of comparison. The transmission rate and energy consumption of receiving data over various radios are benchmarked in Table II.

Considering the scenario shown in Section I, which assumes a mobile user downloads 50 MB movie trailer, Fig. 13 demonstrates the time and energy consumption of using various radio technologies. In the figure, the value of time is shown in the left y-axis and the value of energy consumption in the right. In the results of the case in 3G, data rate follows High-Speed Downlink Packet Access (HSDPA) Category 10 in 3rd Generation Partnership Project (3GPP) Release 5 and we assumed inactivity timer lasts 5 seconds. For the UWBLEE technology the estimated total power consumption for the complete integrated transceiver with digital parts in passive and semi-passive operating modes is multiplied with the factor of 2 in comparison to the power consumption of RF front-end implementation [30]. However, the power consumption of digital parts is highly dependent on the total complexity allowed in passive and semi-passive operating modes, and on the optimized design of integrated circuit. The energy consumption does not include the part of writing data into memory storage in all the cases and only shows the energy consumption of receiving data via different radios. The power consumption of writing in our NoTA-based solution is around 2 nJ/bit for NAND flash and approximate 1–2 nJ/bit for PCM. Both of memories are considered competitive from energy efficiency point-of-view [37].

Based on the calculation, the time spent on downloading the movie trailer is only 8 s and the energy consumption of RF front-end is 0.043 J when using UWBLEE. As mentioned, in the total power consumption for the complete integrated transceiver the power consumption of digital parts must be taken into account. In addition, there is a great difference in the global power consumption of the system in the passive and semi-passive modes although the power consumption of the functions in the mobile phone is equal in the two modes. The reason for this is that in the passive mode the energy for communication is transferred wirelessly, whereas in the semi-passive mode the energy is taken from the battery. The efficiency of the WPT link, mandatory in the passive mode, is highly dependent on the factors such as transfer frequency, size of antennas, and distance, and it is obviously lower than in battery-powered case. Nevertheless, the estimated total energy consumption of downloading the trailer remains below 0.1 J (and below 1 J with the memory access) for UWBLEE in the mobile phone. Comparing other technologies with UWBLEE, the energy consumption of using 3G is up to 72.25 J, where the tail energy accounts for 6% of total energy consumption. Moreover, time consumed on downloading the movie trailer by using Bluetooth and NFC is up to 190.5 s and 417.7 s respectively. No matter from speed and energy saving point of view, our RF memory tag based solution would enable shorter time of downloading ubimedia content, better user experience, as well as smaller energy consumption.

V. Discussion and Conclusions

The RF memory tag (i.e., mobile reader/writer and tag) solution was developed and tested in the MINAmI project. Implementation is shown in Fig. 14. The development of a RF memory tag sub-system of MINAmI project is based on a flexible, field-programmable gate array (FPGA) based hardware platform. The sub-system takes benefit from the ultra-low power UWBLEE transceiver architecture, which is suitable for data rates required in RF memory tag applications. The technical results are promising and useful for the concept of mobile-phone-readable RF memory tags. The data-rate of 112 Mbit/s has been achieved over the novel radio interface in technical demonstrations [30]. This leaves

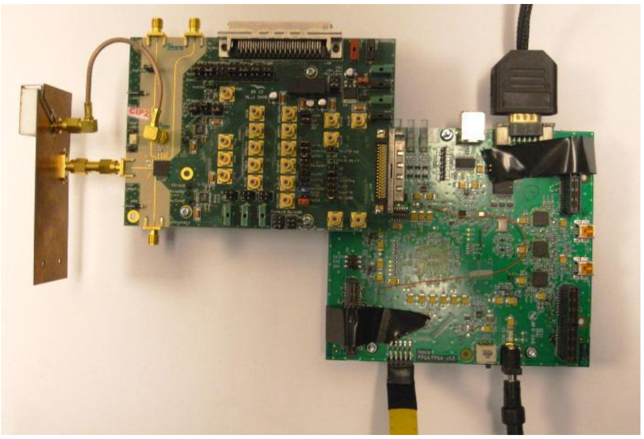

Figure 14. Our UWBLEE implementation

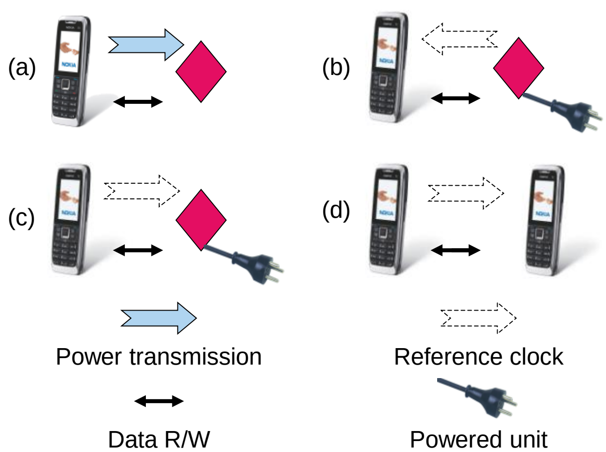

Figure 15. Some possible operational combinations of mobile phones interacting with RF memory tags.

room for up to 50% protocol and memory access overhead when targeting 50 Mbit/s end-to-end communications. On the PHY and MAC layers short target distance and point-to-point communication efficiently minimize the protocol overhead on packet level. However, efficient pipelining in buffering of the data is in crucial role in optimization of the end-to-end system. The third important factor is the memory access speed. This is relevant when reading data from the source memory and when writing the data to the target storage memory. As shown in Section III, the continuous development of NVM memories will provide power-efficient and fast solutions for the target applications. Altogether, the listed factors and the results achieved with the demonstration platform show that mobile reader/writer and the high capacity memory tag is implementable.

A. *Future development*

The UWBLEE wireless connection technology presented in this paper provides data rates significantly exceeding the existing NFC technology already in the market. From technology ecosystem point-of-view there is little sense in developing UWBLEE as an independent technology. UWBLEE can thus be seen as a possible future high-speed extension to existing RFID or NFC technologies.

As the range of this wireless interface is fairly short, in the range of 10 cm, there exist use-cases similar to the NFC use cases (range touch to 3 cm). Physical selection [38] by touching of a service-providing tag is thus possible. In such use, the tag would be marked with a logo of the corresponding service, such as title or picture of a movie or a magazine, making selection of the service intuitive and easy.

The possibility of using a mobile phone to read a passive tag is, naturally, not the only operational combination of these devices, as shown in Fig. 15, where (a) refers to a phone reading a RF memory tag, (b) to Internet kiosk based on a RF memory tag, (c) is a variant of (b), and (d) refers to data transfer between mobile phones. In a multi-device environment one device can work as a proxy for the memory tag and provide other devices with access to its services [11]. There are also possibilities to have memory tags with their own power sources, which eliminate the need of wireless powering. In that case, the reading range can be extended or power use within the mobile phone can be reduced. The phone can also communicate directly with other similarly equipped phones.

Our RF memory tag solution supports Nokia's *Explore and Share* concept, a new way of transferring content (e.g., multimedia, maps, and applications) to a mobile phone [12]. RF memory tags feed users appetite for ever increasing local bandwidth and capacity requirements. Users would, naturally, invent new use cases and ways of utilizing these tags in the local content delivery domain. These *Express Tags* can explore new large content shared by others [39]. NoTA is well positioned in the transport agnostic technology. It fits to the many inter-device use cases, such as in ubiquitous world.

Our vision is that there is an ever-increasing need to move content from the Internet to mobile devices and vice versa, as well as between devices. The amount of available energy to support all this wireless traffic is not increasing correspondingly, however. Thus, possibility to distribute the energy consumption of wireless connections so that either of the endpoints takes care of most of the power usage is an interesting enabler to future applications.

B. *Conclusions*

The evolution of non-volatile memory technologies gives the basis for the vision about RF memory tags. However, the large memory creates a need for a high-speed data connection that can be used to transfer the contents of the tags in a timeframe acceptable for the user. The dual-band radio interface, UWBLEE introduced in this paper provides the required data rate and possibility for future scalability as memory sizes become larger.

Modular architecture is mandatory in the RF memory tag system to optimize performance. For example, latencies common in memory access of centralized systems are not acceptable. Power consumption of the mobile reader/writer is efficiently minimized with an independent sub-system keeping the involvement of the main processor at the minimum. In contrast to conventional radio systems, the main processor only triggers the communication and the independent subsystem handles the transfer and storage of the data. Thus, the main processor does not have to be involved in the low level communication processes.

In addition to the RF memory tag reader/writer capability in mobile devices, mobile devices can be also equipped with embedded RF memory tags. This enables a new usage scenario called internet kiosk which can be further used to enable internet connection seemingly with zero power consumption in the mobile device.

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